Energetic Phenomena I

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Topics:
Overview of the Energetic Phenomena on the Sun
Solar magnetism and activity
Open and closed field Structures
coronal holes, active regions, and filament regions
flares and CMEs

Energetic Phenomena

- Flares, CMEs, energetic particles, solar wind
- Origin: Magnetic Field
- Mechanism: Release of free energy, particle and plasma acceleration
- Physical Processes: plasma instabilities, magnetic reconnection, collisionless shocks
- Consequences: control of the large-scale structure of the heliosphere, cosmic ray modulation, space weather (radiation hazard to space activities; communication navigation impact; ozone layer, cloud cover; power grids, even pipelines);

How Energetic?

- Coronal mass ejections: up to 10^{26} J
- Flares up to 10^{25} J (electromagnetic)
- Solar Energetic particles:
- Electrons in the MeV range
- protons, heavier ions in the GeV range
- Solar Wind up to 700 km/s

Energy Magnitude

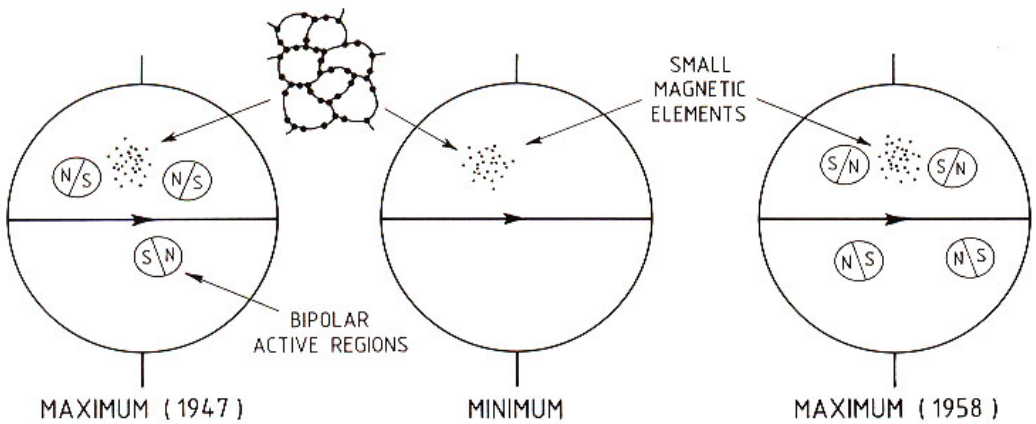
- Fastest CMEs have KE ~ 10^{26} J
- Sun's remaining life ~ 5 billion years (1.6 x10^{17} s.
- 1 GW generator working over the lifetime of the Sun generates the energy equivalent of a CME

Energy Partition ($\log_{10}$ ergs)

Magnetic		32.3
Flare	Electrons	31.3
	Ions	<31.6
	Thermal Plasma	31.1
	Radiant	31.3
CME	Kinetic	32.3
	Gravitational	30.7
Energetic Particles	at 1AU	31.5
Solar Wind	Through 1AU Sphere per Day	32.2

Surface Magnetic Field

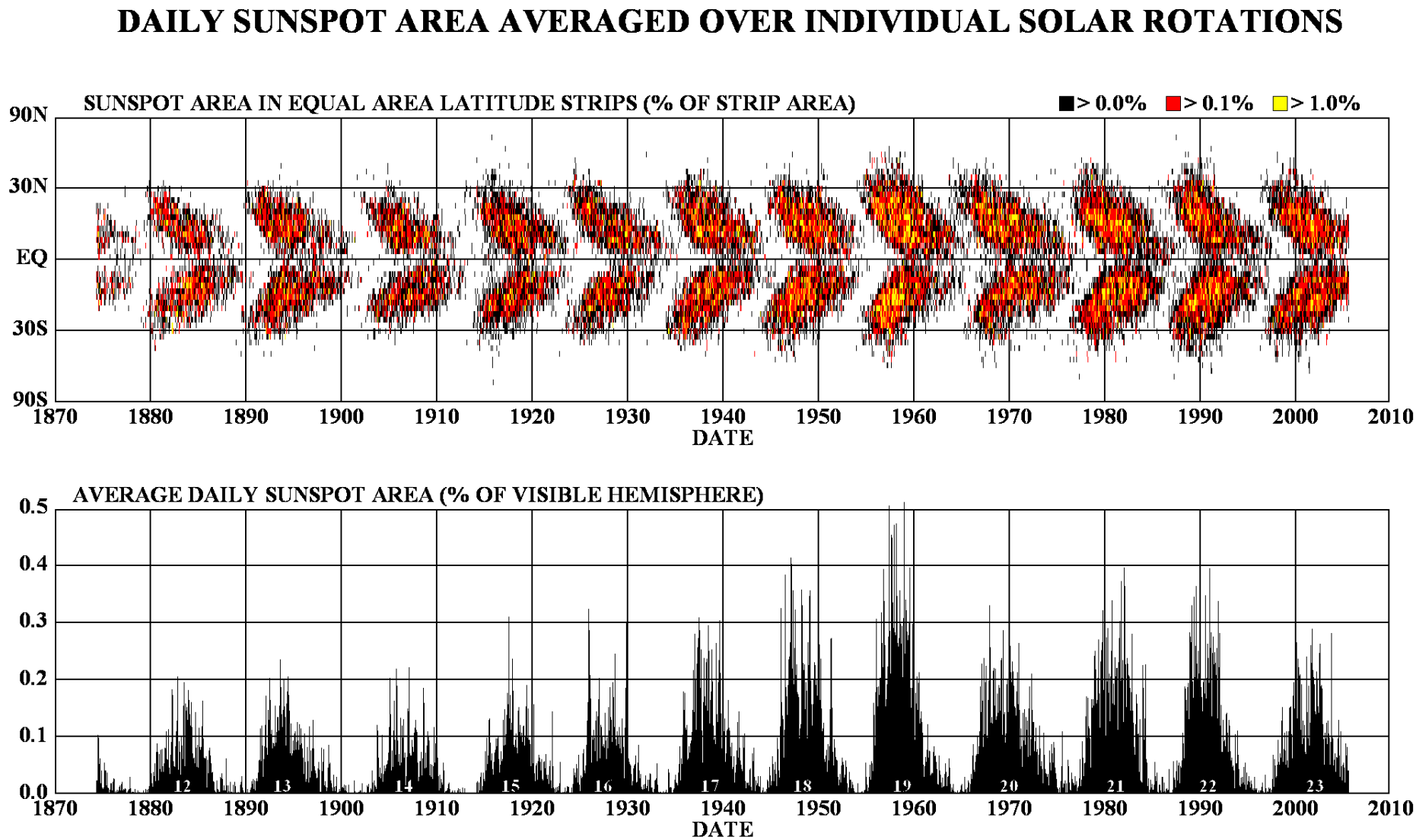
- The photospheric field is organized in patches of strong field embedded in an overall weak field. The strong field has a hierarchy of magnetic elements with same field strength but different fluxes. Sunspots (3000 G; 10^22 Mx)) to bright network elements (~1500 G 10^18 Mx).
- During solar maxima, the large scale field is in active regions (ARs): two spots of opposite polarity surrounded by faculae. Occur in bands parallel to the equator (active region belts).
- Hale's Law: tendency of leading polarity in the active region fields to differ in northern and southern hemispheres
- ARs originate from CZ and decay in a few months as small-scale magnetic elements
- ARs tend to originate in the sites of existing or previous ARs
- AR emergence in the butterfly pattern: the solar cycle can be regarded as a wave with a period of 22 years



Hoyng, 1992

Butterfly Diagram

AR emergence at ~40 deg in new cycle
Emergence at progressively lower latitudes



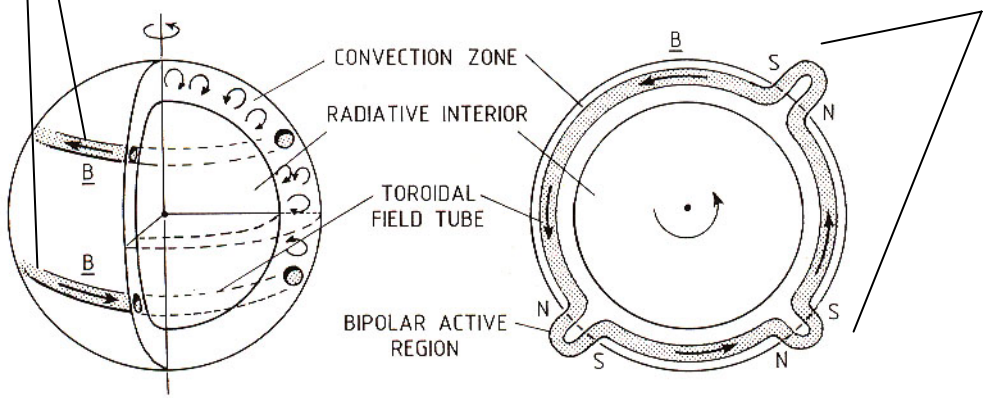
http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif

NASA/NSSTC/HATHAWAY 2005/10

Flux emergence

- Flux emergence is the key to the connection between magnetic field generation in the Sun, and its consequence on the surface and above.
- Assume an east-west flux tube is embedded in the CZ which has a fluid pressure p_i. The magnetic field itself has a pressure, $B^2/8\pi$. For pressure balance, $p_e = p_i + B^2/8\pi$, where p_e & p_i are external and internal gas pressures. Since $B^2/8\pi > 0$, $p_e > p_i$, so the buoyancy force will lift the flux tube to low density region. Penetration of this field through the solar surface produces the observed bipolar structure.
- How the east-west flux rope is produced inside the Sun is the business of the dynamo theorists.

The two tubes reach equator in 11 years and disappear

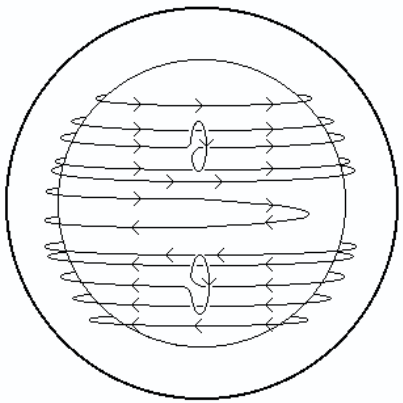


Hale's Polarity law

Dynamo: α–Ω dynamo

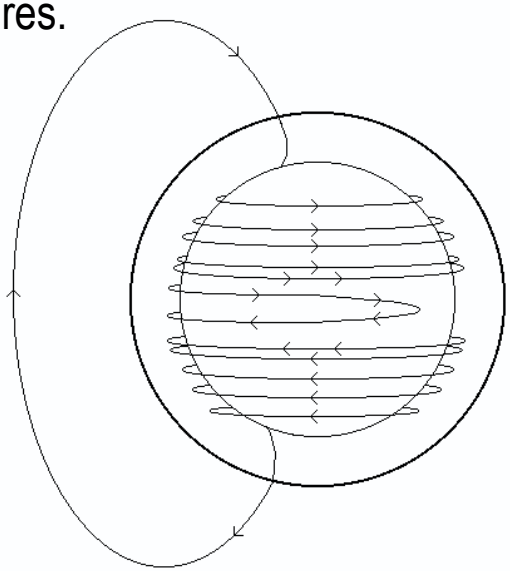
Twisting of field lines is caused by the effect of the Sun's rotation on the rising "tubes" of magnetic field from deep within the Sun. This is called the alpha-effect after the Greek letter that looks like a twisted loop. The twist produced by the alpha effect makes sunspot groups that obey Joy's law and also makes the magnetic field reverse from one sunspot cycle to the next (Hale's law).

Hathaway



The α-effect

Magnetic fields within the Sun are stretched out and wound around the Sun by differential rotation. This is called the omega-effect after the Greek letter used to represent rotation. It takes ~8 months for a north-south field line to wrap once around the Sun. The field will have different directions in the northern and southern hemispheres.

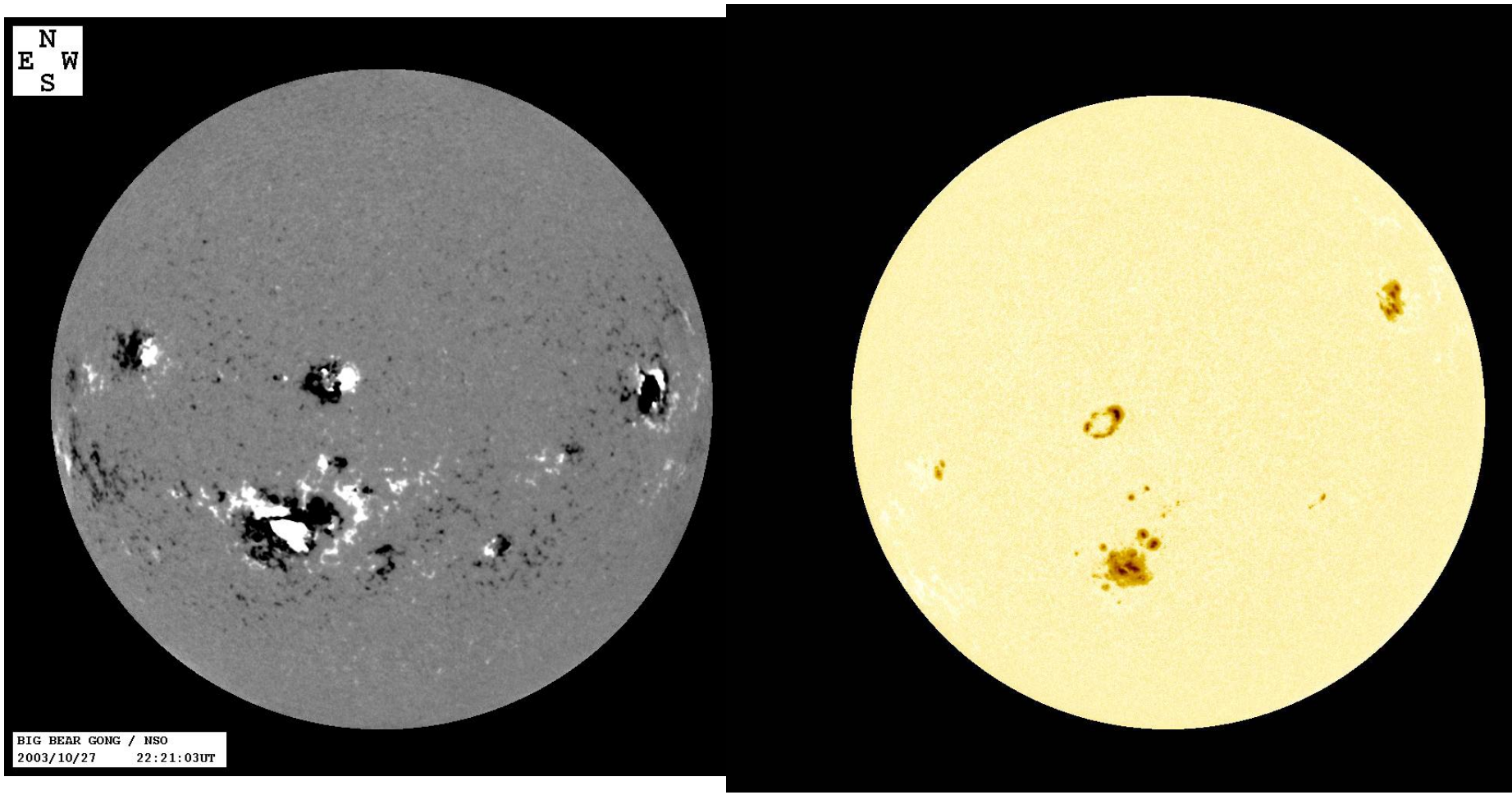


The ω-effect

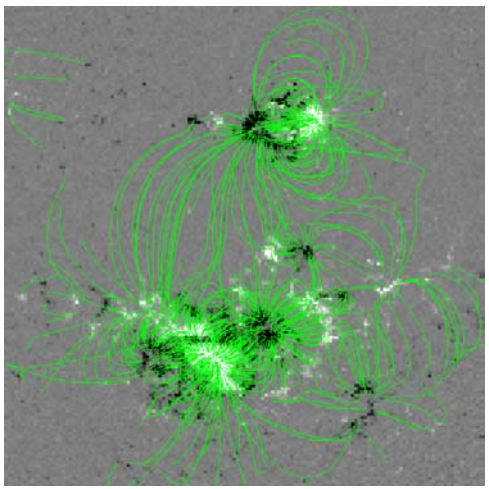
Animation

This animation illustrates how differential rotation converts poloidal flux into toroidal flux

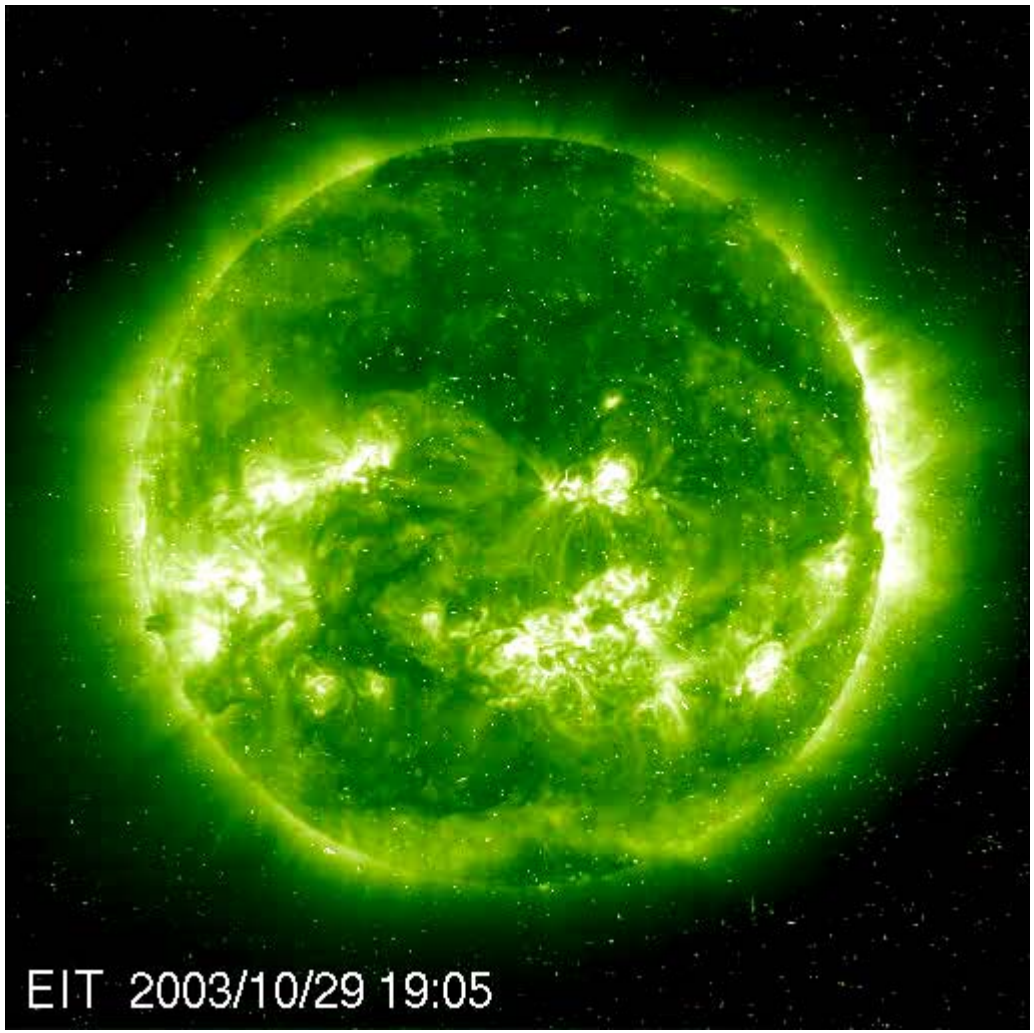
Active Regions



Change in AR

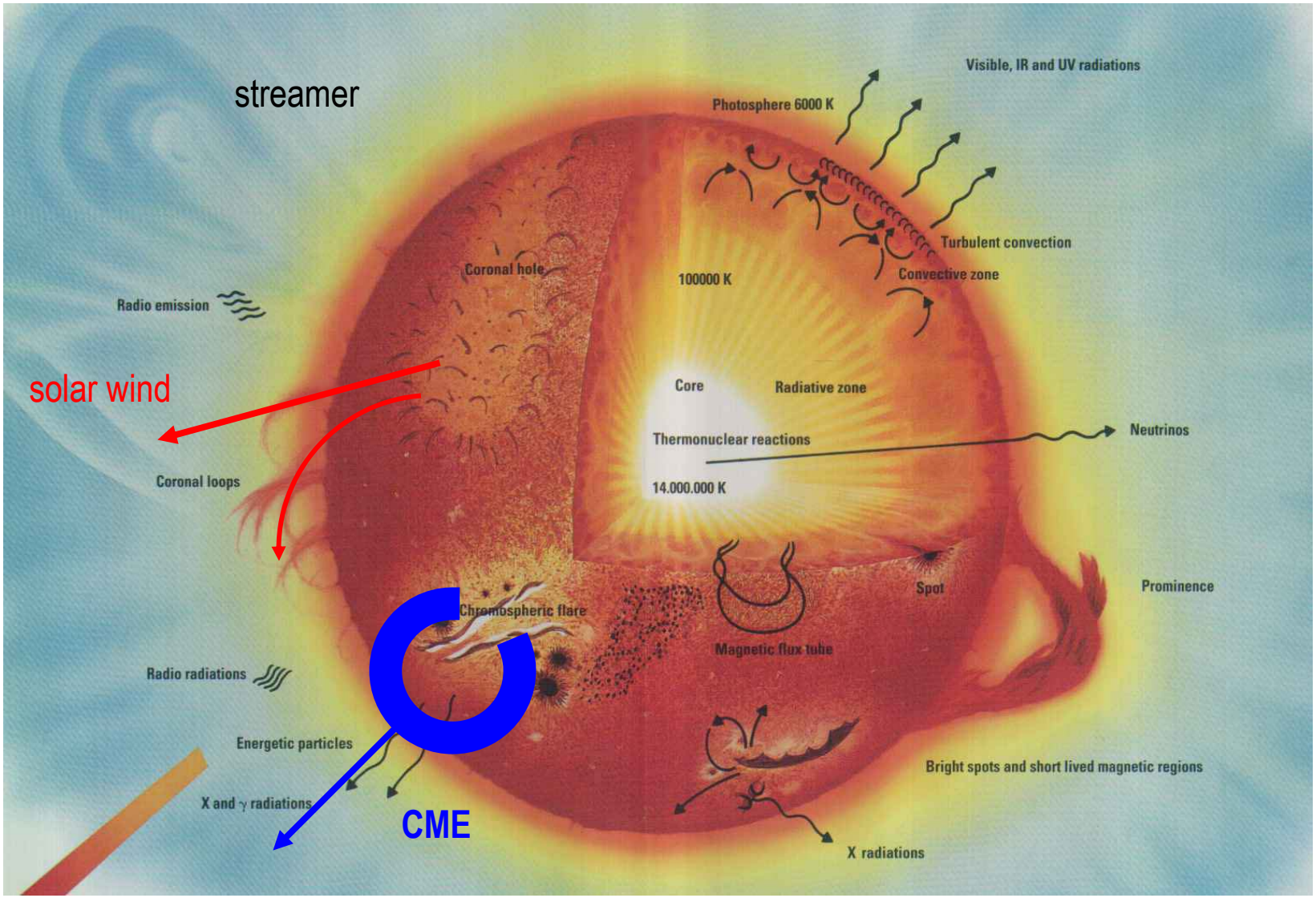


Gopalswamy et al. 2005



Overview of the Sun

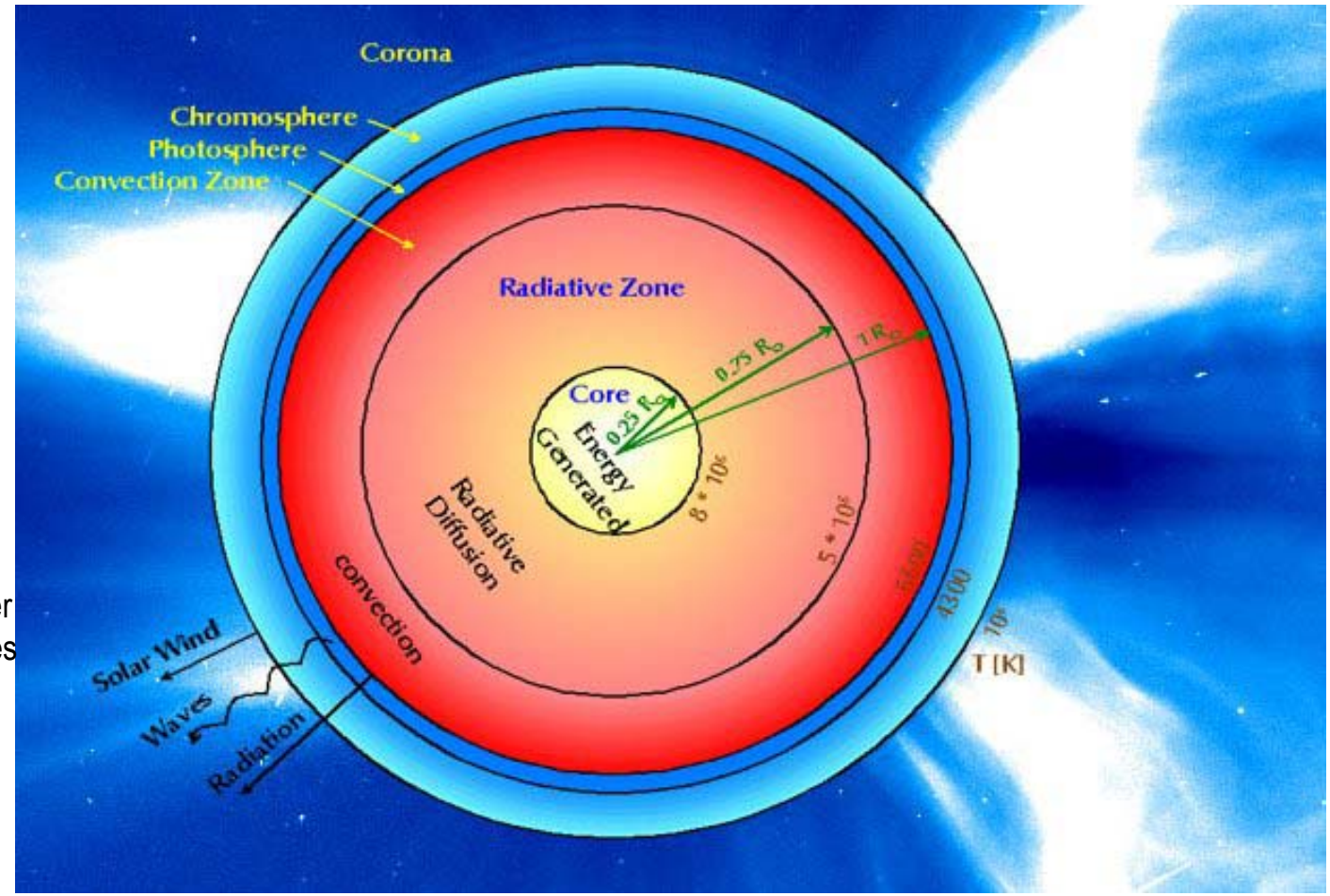
A summary of what we know about the Sun from the interior to the atmosphere with various types of electromagnetic radiation and the mass emissions. Coronal mass ejections (CMEs), solar wind and solar energetic particles (SEPs) represent mass emissions



Solar Layers

The structure of the Sun
Consists of seven "layers"
- the core (energy generated)
- the radiative zone
- the convection zone
- the photosphere
- the chromosphere
- the transition zone
- the corona

The transition zone is a thin layer
Where the temperature increases
From tens of thousands of K to
A million K over a very short
distance



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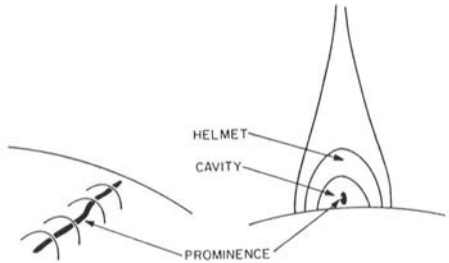
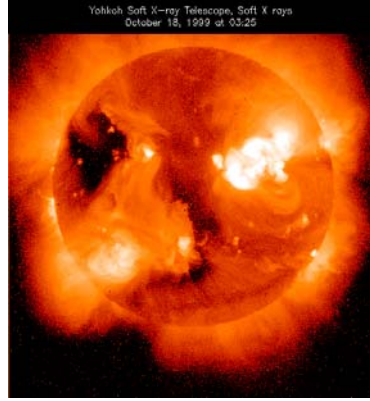
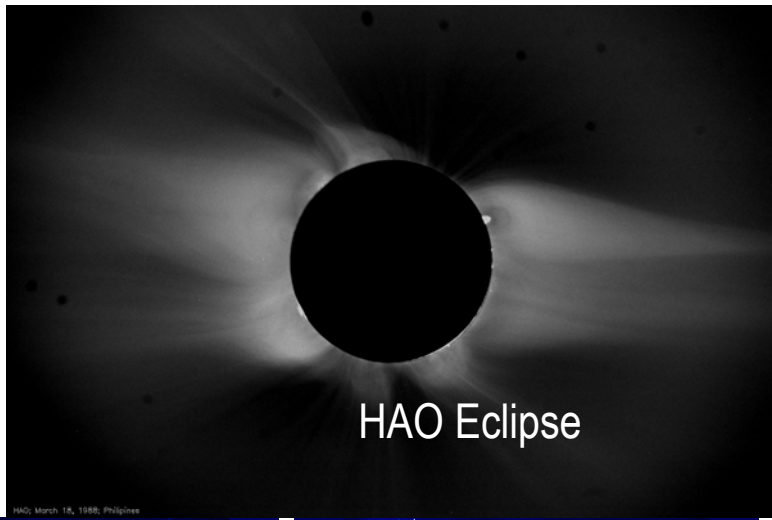
Coronal Features

- Coronal Holes : source of high-speed solar wind
- Coronal Loops: closed magnetic field line loops around sunspots and active regions. can last for day or weeks if not associated with solar flares
- Helmet Streamers: source of low-speed solar wind; network of magnetic loops with dense plasma connecting the sunspots in active regions typically occurring above prominences
- Polar Plumes: long thin streamers associated with open magnetic field lines at the poles. Plume and interplume regions have different properties near the Sun. fast wind in the interplume region
- Coronal Mass Ejections (CME): huge magnetized plasma structures ejected from the Sun over the course of several hours
- Solar flares: huge explosions with time scales of only a few minutes

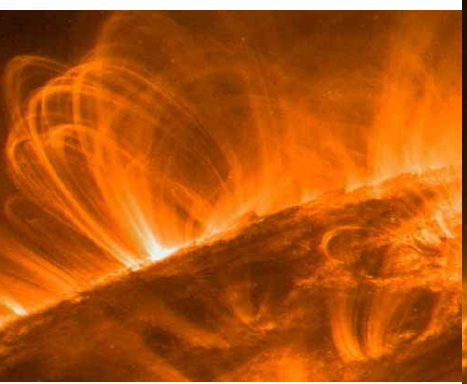


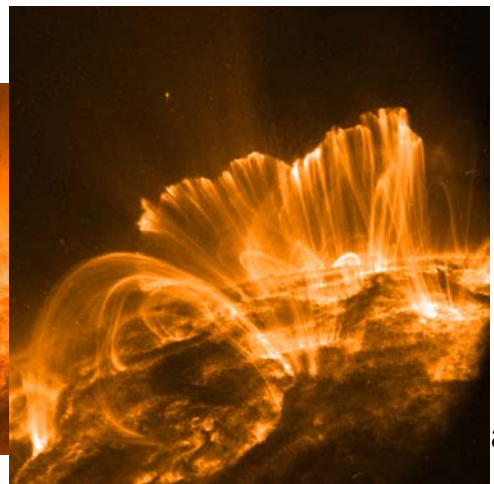


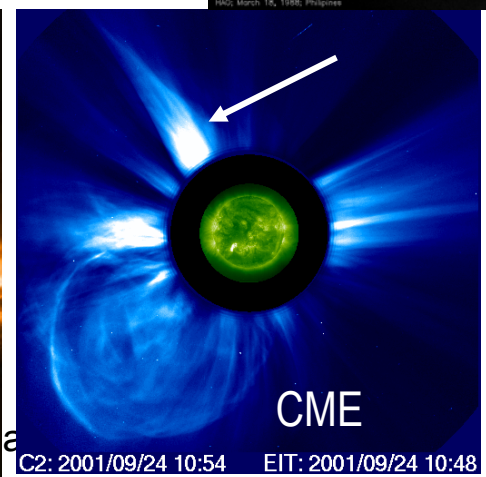


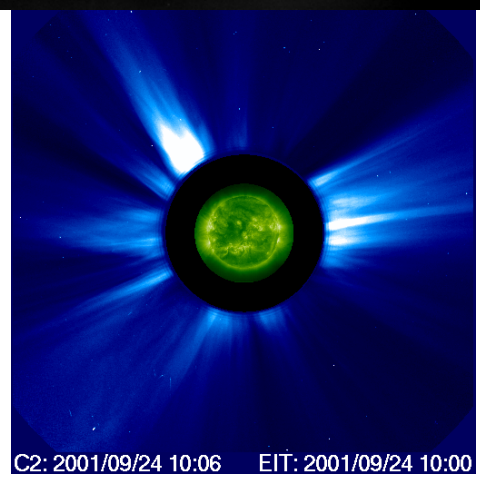
TRACE Flare loops

TRACE loops



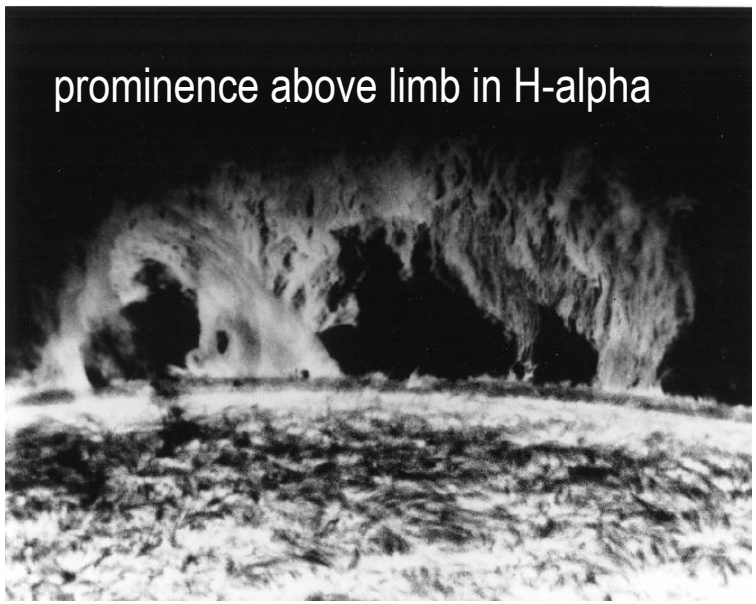




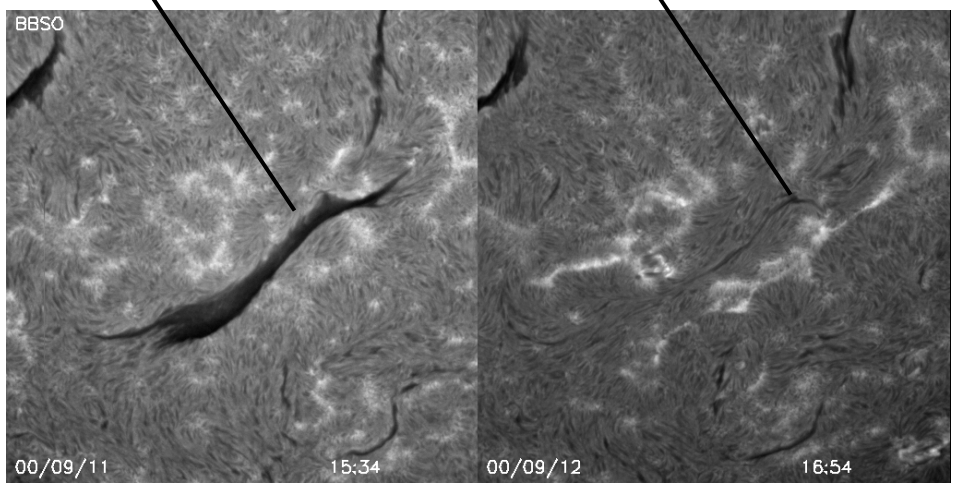


Prominences & Filaments

Prominences: dense clouds of cool material (~7000K) suspended in the corona by loops of magnetic field. Prominences and filaments are actually the same things except that prominences are seen projecting out above the limb of the Sun. Both filaments and prominences can remain in a quiescent state for days or weeks. However, as the magnetic loops that support them slowly change, filaments and prominences can erupt and rise off of the Sun over the course of a few minutes or hours.



Dark Filament on the disk & its disappearance (eruption)



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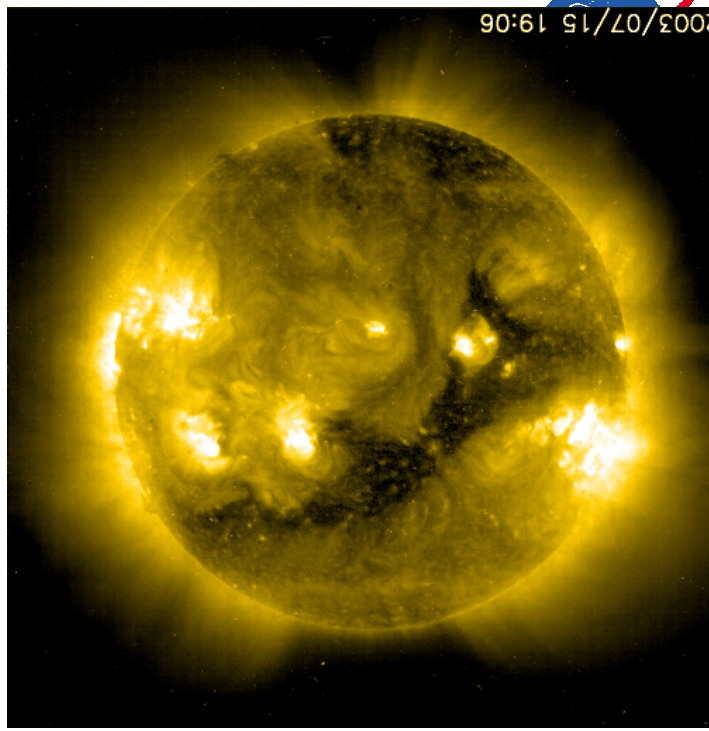
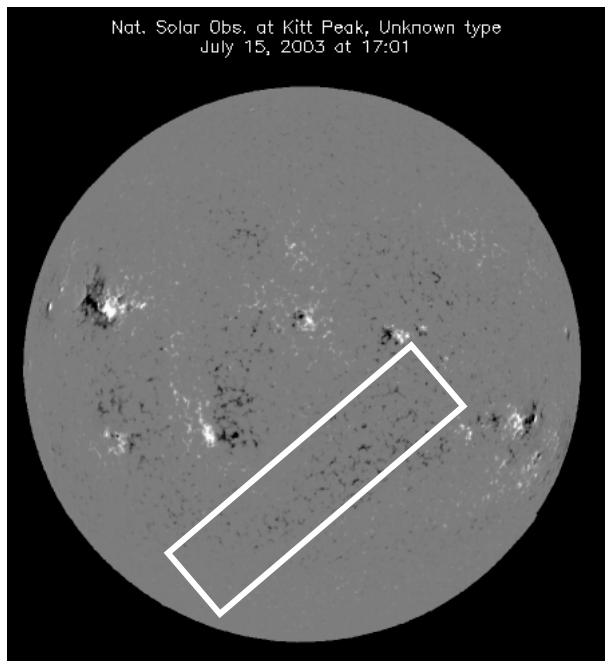
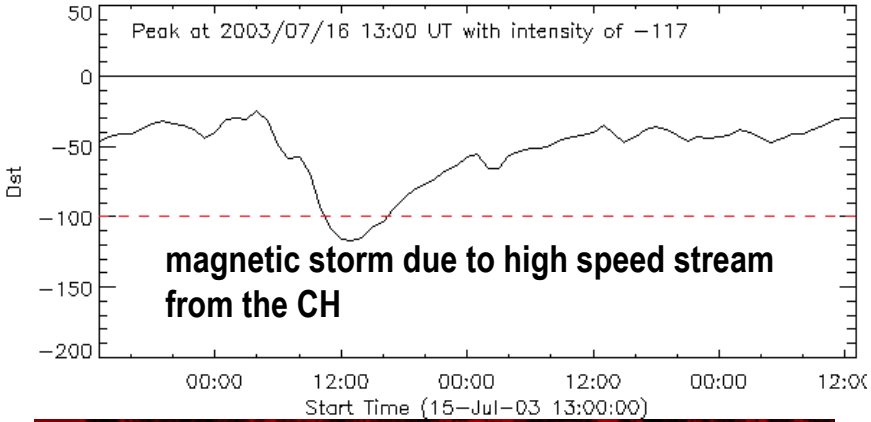
Coronal Holes

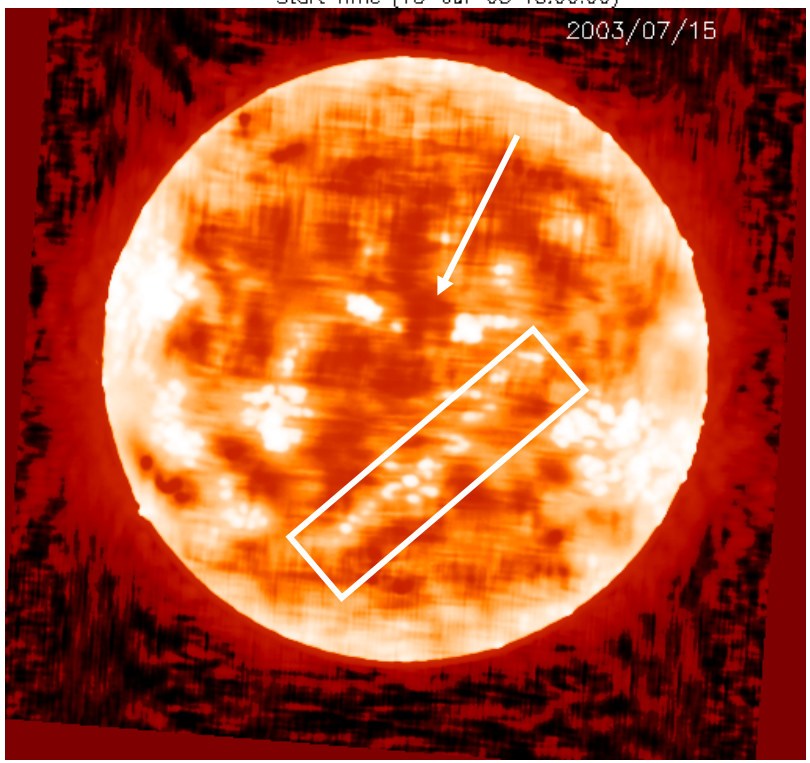
- Large-scale regions of the corona observable in X-rays (a few Å) & EUV fainter than the surrounding corona.
- Polar CHs can cover up to 10% of solar surface; low-latitude ones from 1 to 5%
- Polar holes, largest during solar minimum shrink toward and disappear during solar maxima
- Unlike sunspots, CHs display rigid rotation (27 days)
- The formation of coronal holes are linked to the evolution of active regions. The unipolar regions in CH are due to the mergers of the similar polarity regions of active regions (Timothy, 1975)
- Extended NS holes occur when low-latitude holes link up with the polar hole of the same polarity
- The coronal holes have a higher unipolar flux compared to the surrounding quiet Sun
- Bartol called these M-regions from which high speed winds originate. Skylab observations confirmed this
- The transition region is ~5 times thicker in CH than in quiet regions; dT/dz is ~5-10 times lower; pressure is 2-3 times lower
- Coronal hole chromosphere different from quiet chromosphere observed in microwaves





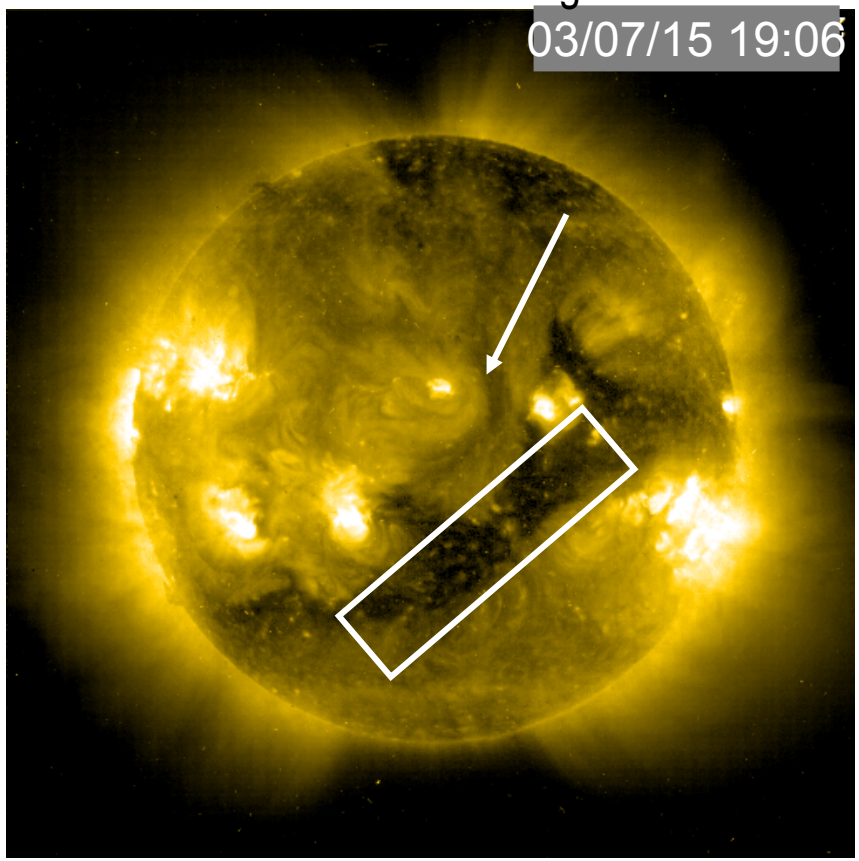
Coronal Holes & Geomagnetic Storms



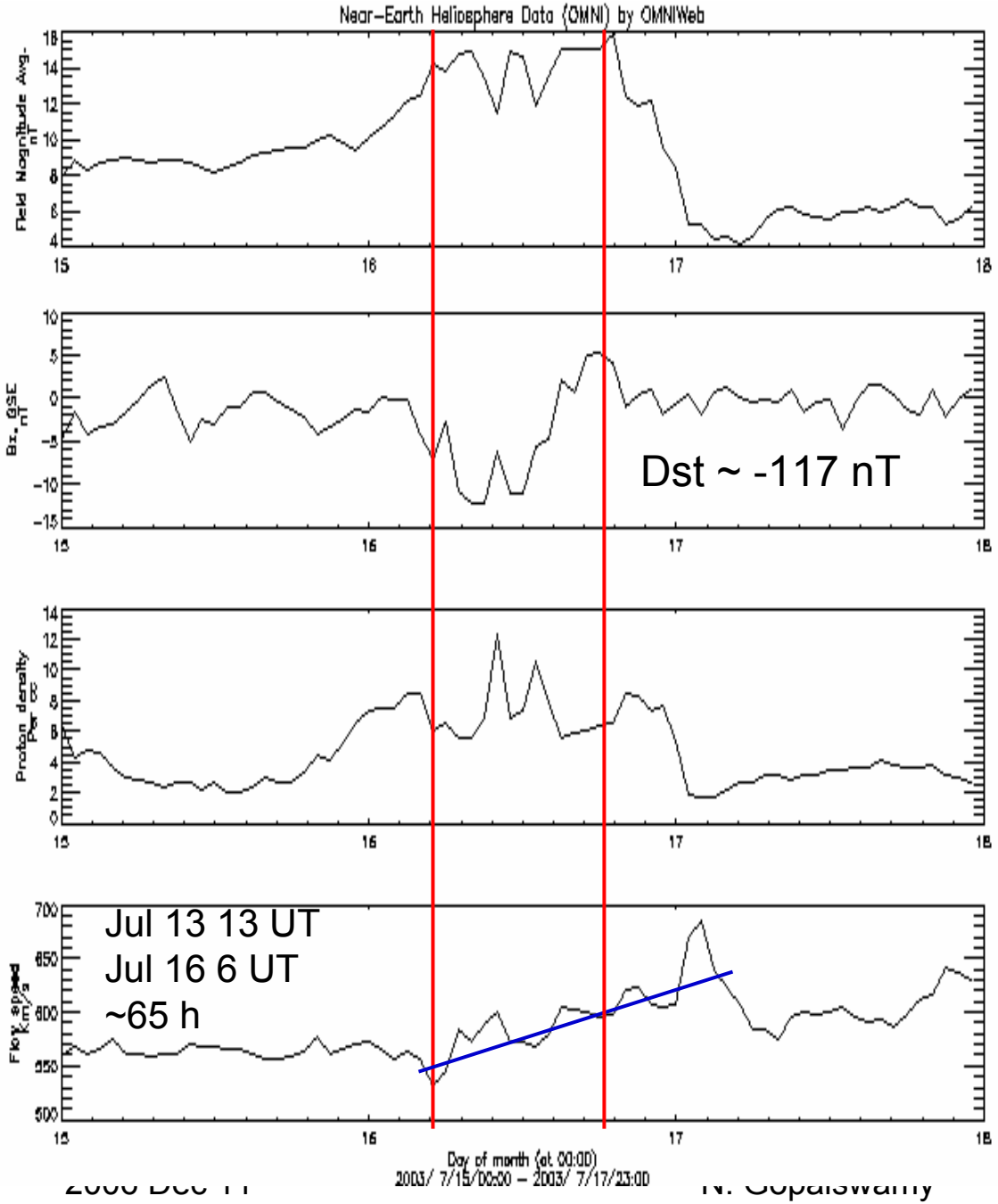


Nobeyama Radioheliograph 17 GHz image; Filament is dark unlike coronal hole. There is something special about the chromosphere under coronal holes: hotter?

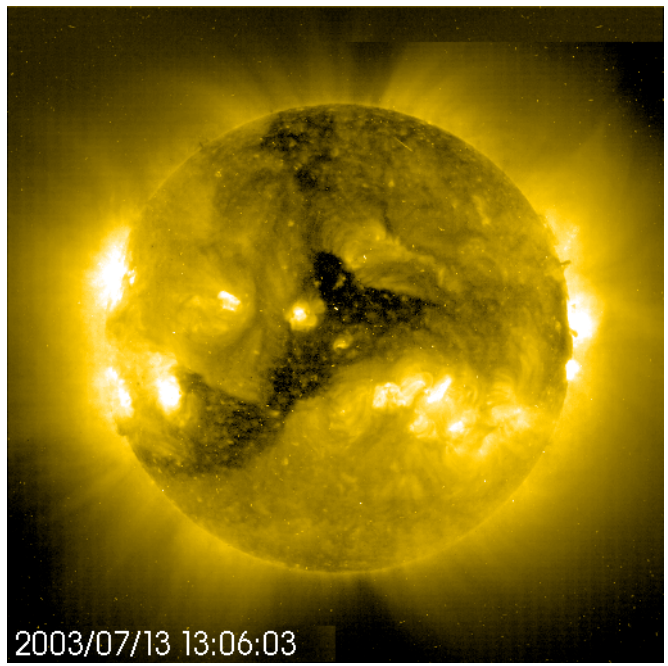
SOHO/EIT 284 A image



Filament is dark as coronal hole

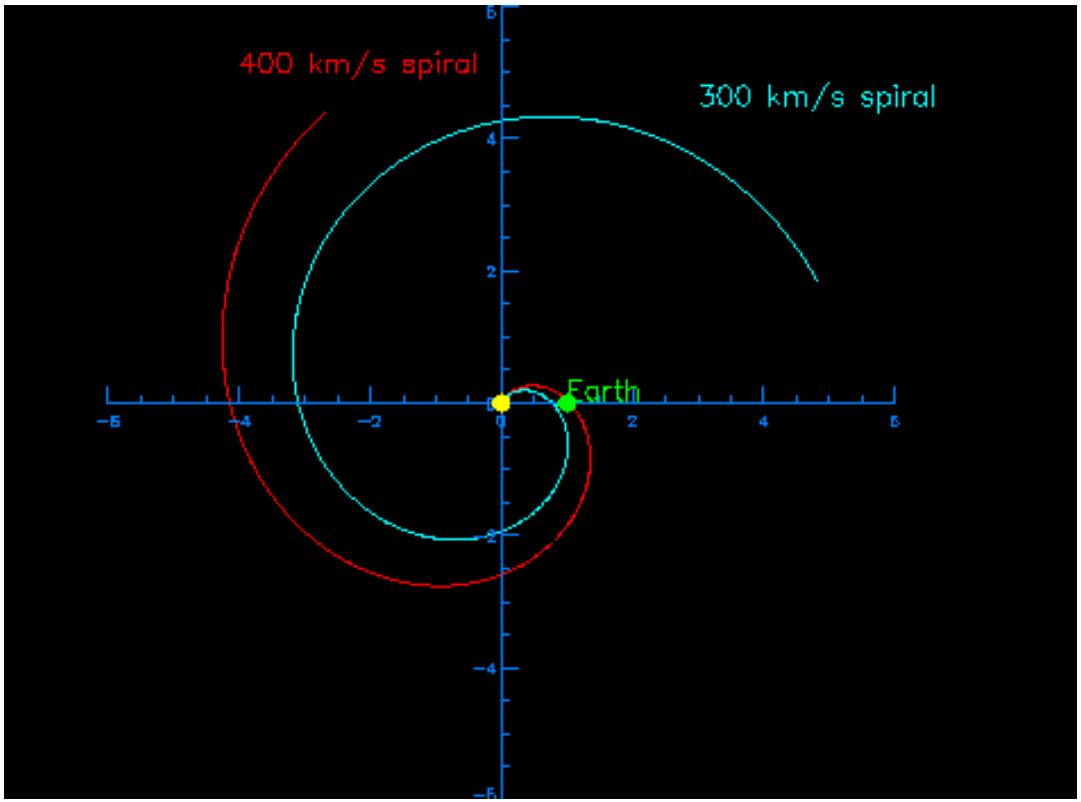


Coronal Holes & High Speed Streams



69 h for the 600 km/s plasma to reach Earth

Archimedean Spirals



The inner heliosphere consists of low energy particles (H, He, etc), magnetic field, particles at relativistic energies and dust.

In this section we introduce the concept of a large-scale organization of the solar wind plasma.

The gas energy density dominates in this regime. As a result of this property, the field is "frozen" in to the orientation that it had when the gas left the corona.

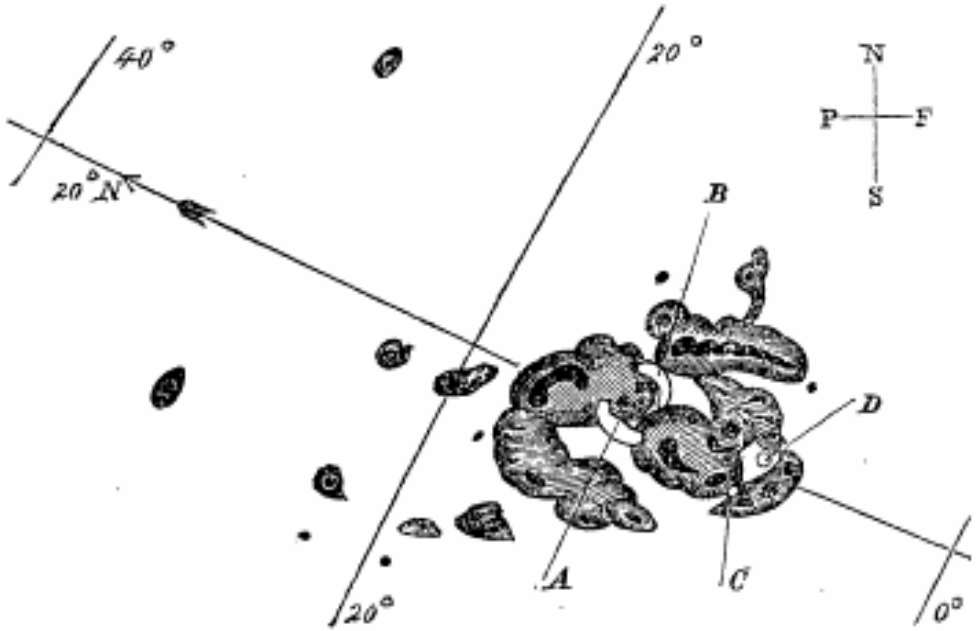
The gas flows out radially (except for the transverse component caused by the solar rotation).

But because of the solar rotation the radial magnetic field becomes an Archimedean Spiral

The orientation of the field is dependent on the speed of the outflow

Discovery of a Solar Flare

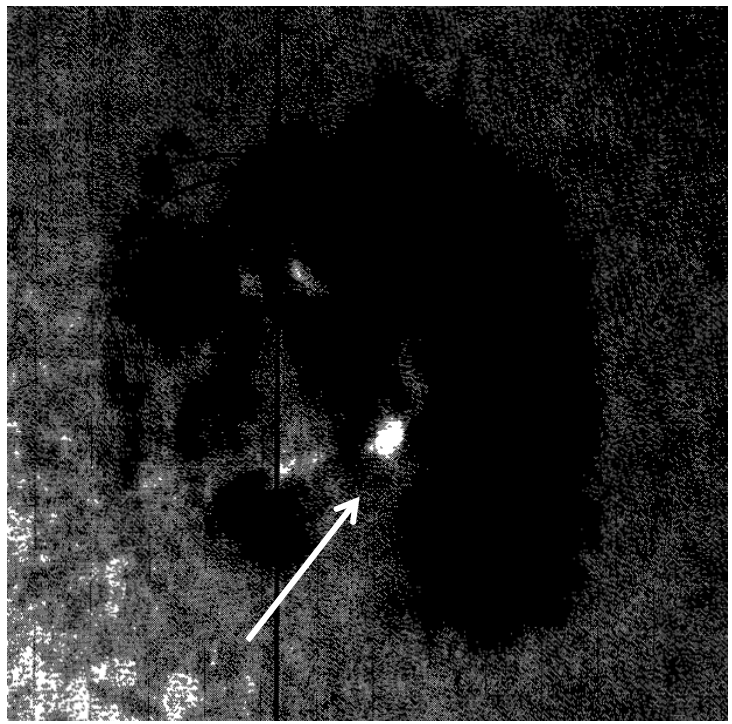
- September 1, 1859
- Independently observed by R. C. Carrington and R. Hodgson
- Magnetic storm commenced early on September 2



Drawing by Carrington

White Light Flares

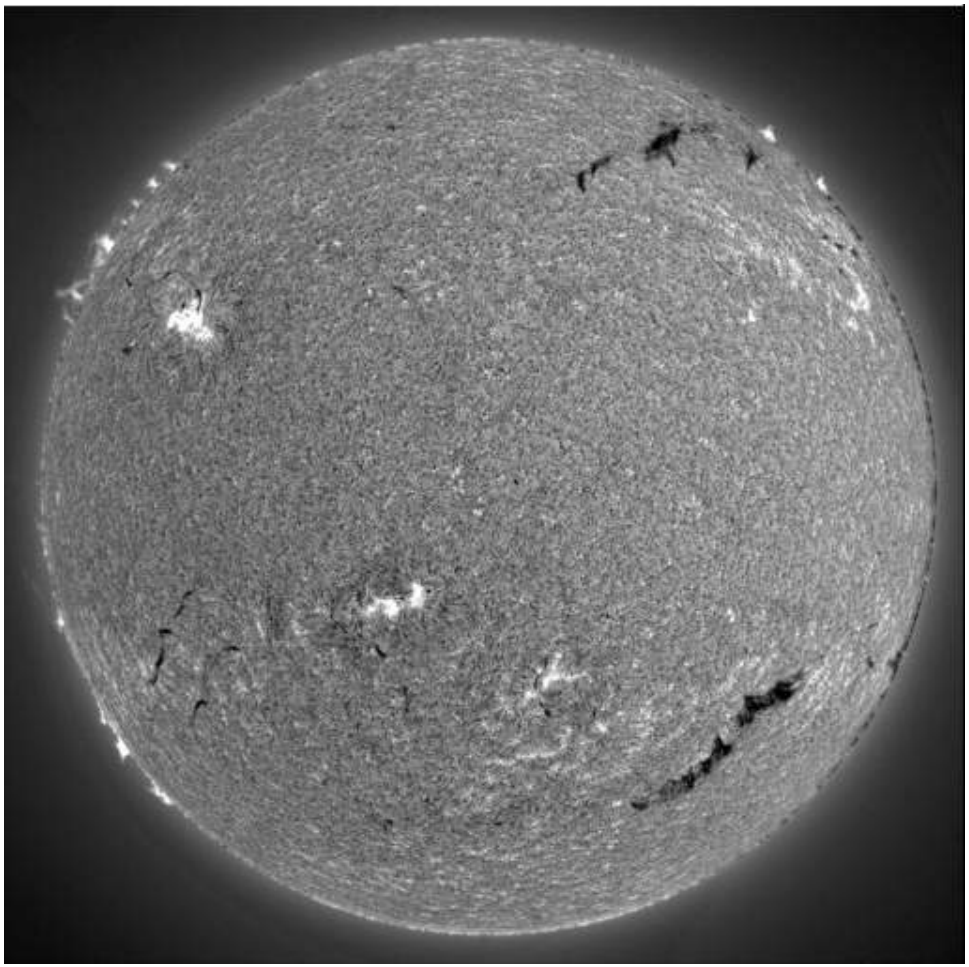
- At most 50% brighter than the solar disk
- Typical energy released in a large flare: 10^{25} J
- Solar Luminosity: 4×10^{26} W
- Exciter: nonthermal electrons and/or protons



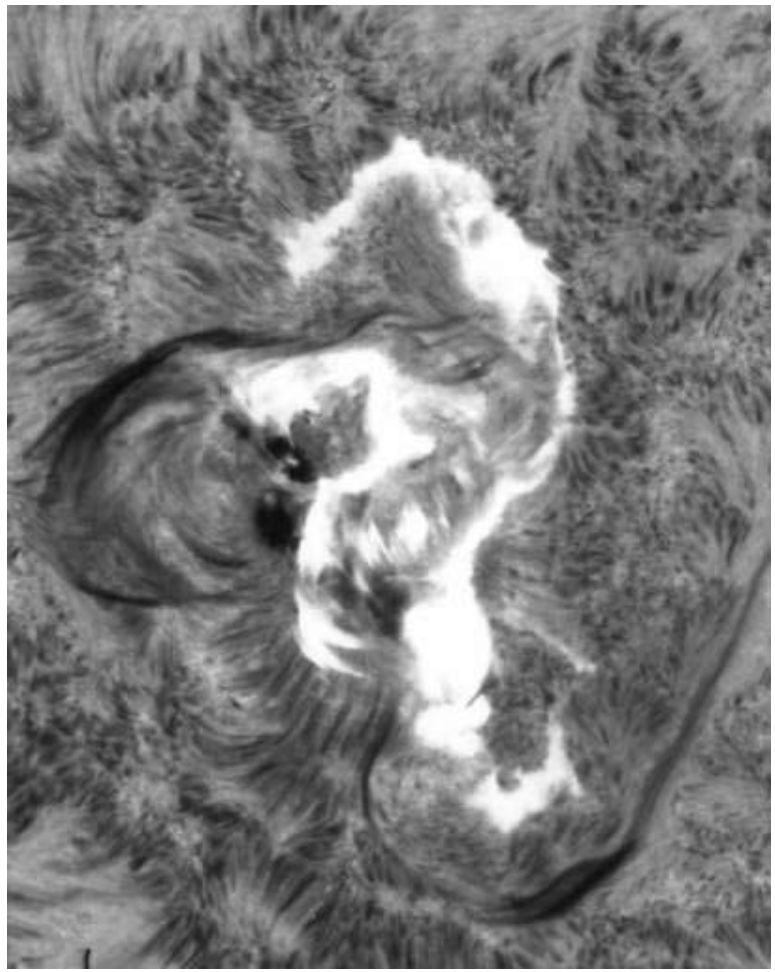
Machado & Rust, *Solar Physics*, 1974

H α Flares

The Sun in H α



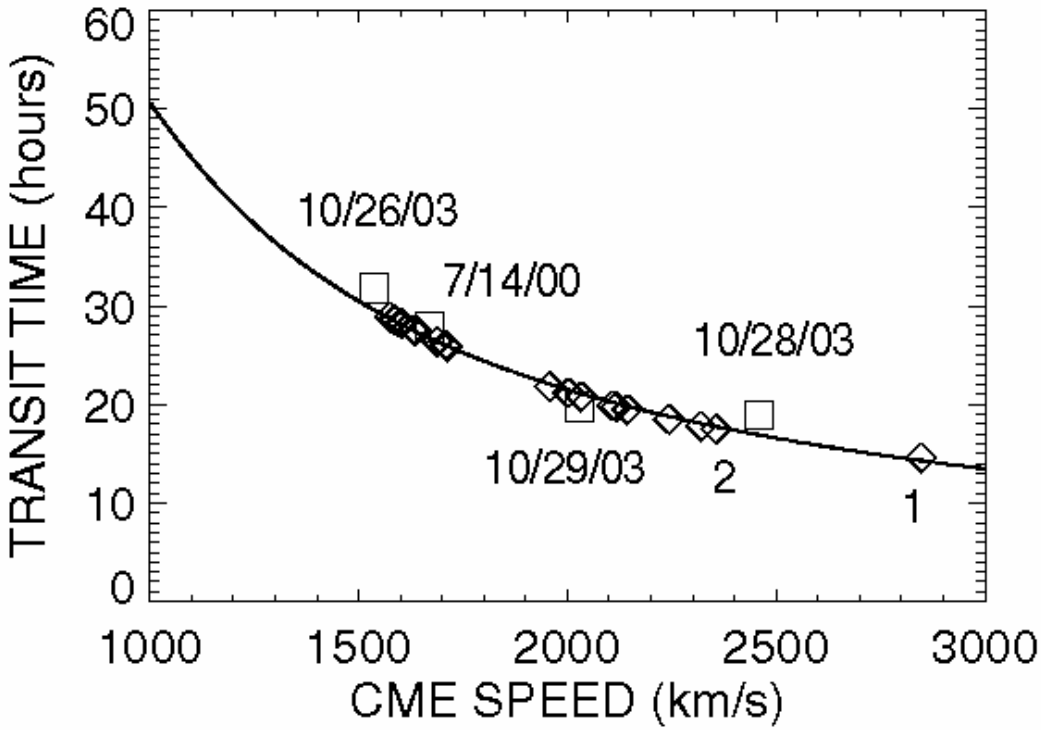
7 August 1972 Flare



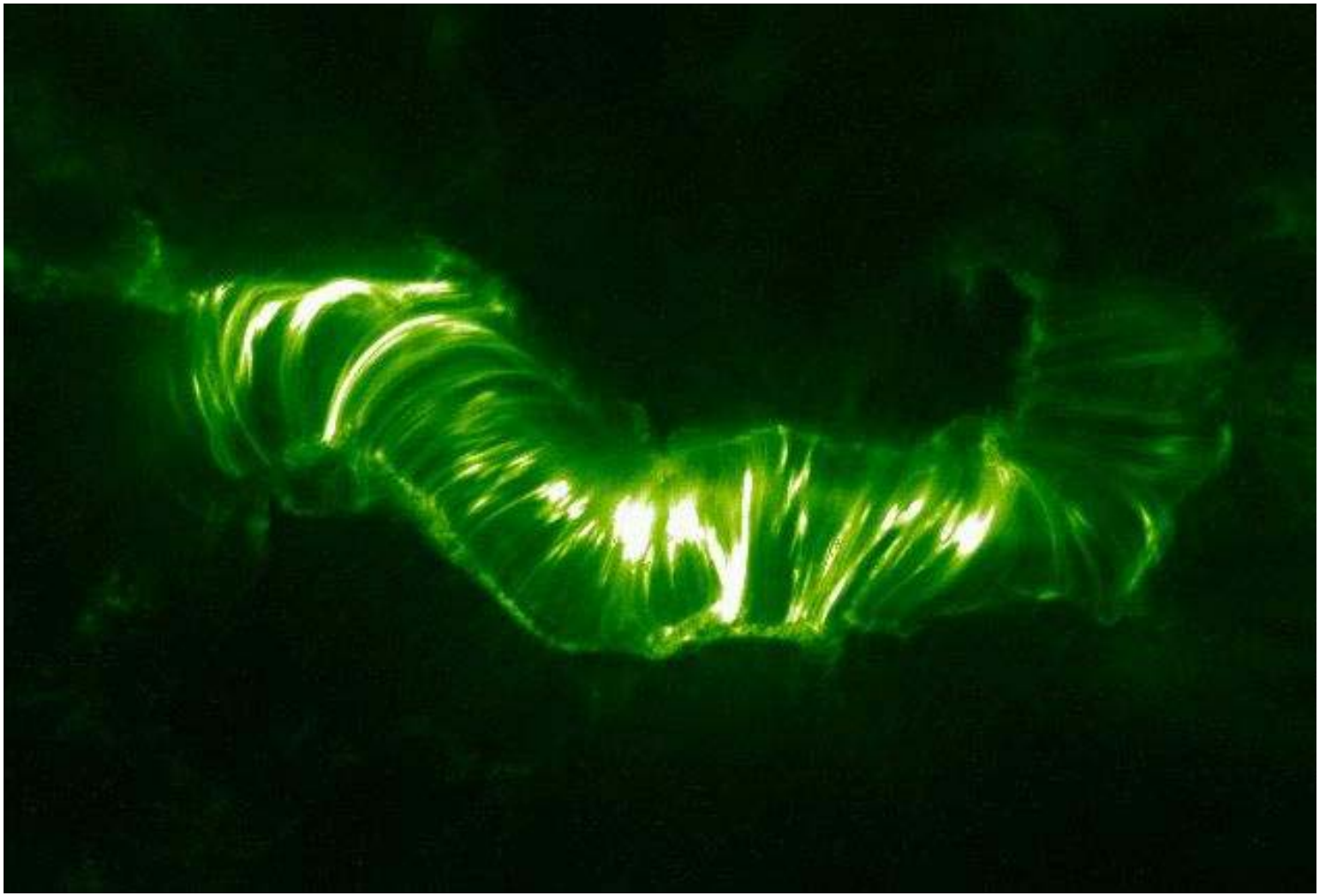
Big Bear Solar Observatory

Sun-Earth Connection

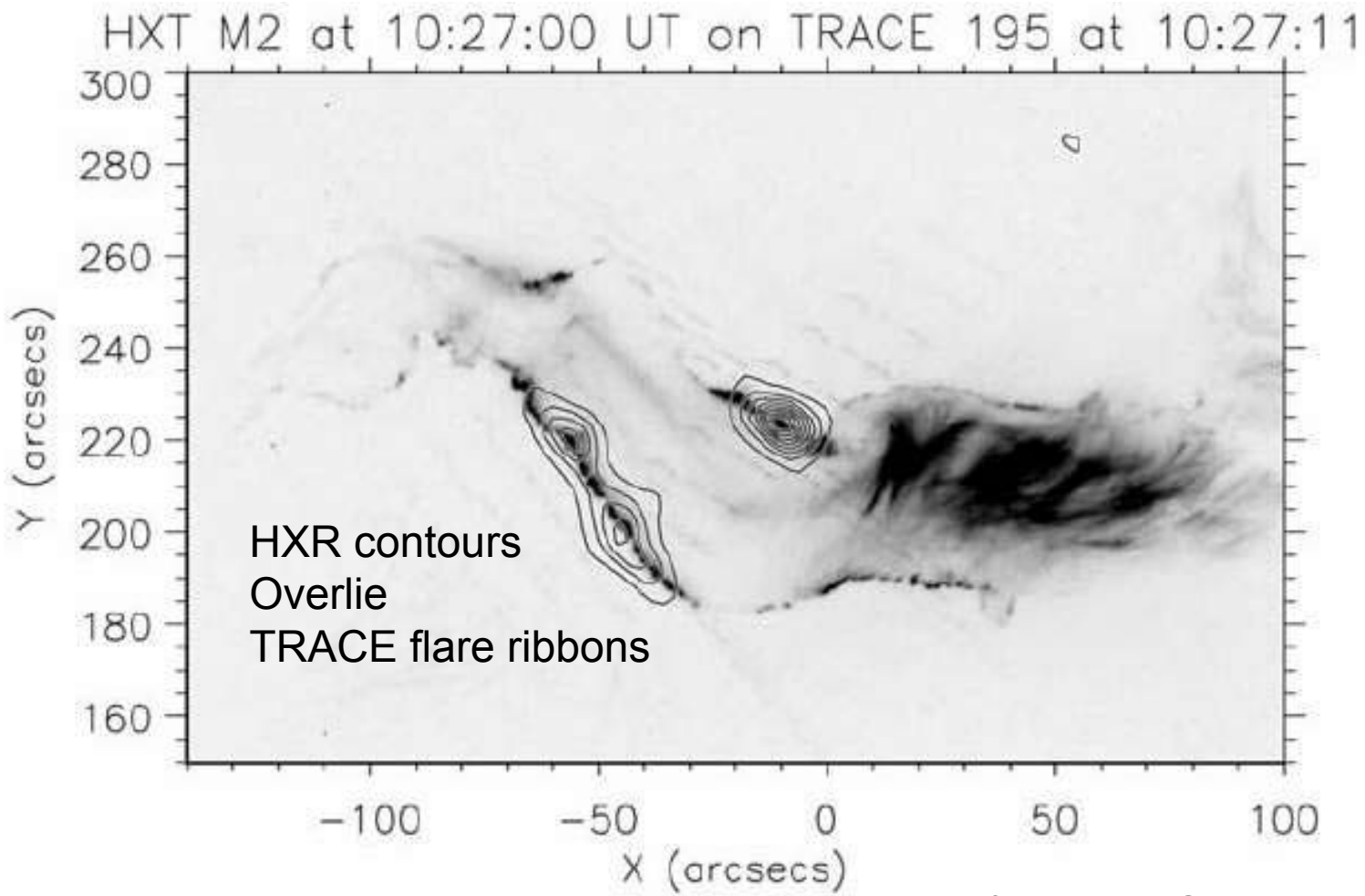
Travel time of interplanetary shocks as a function of CME speed
1: August 1972 event; 2: Carrington event of September 1859



Post-eruption Arcade 14 July 2000 “Bastille Day” Flare



Flare Ribbons (TRACE) and Hard X-Rays (Yohkoh)

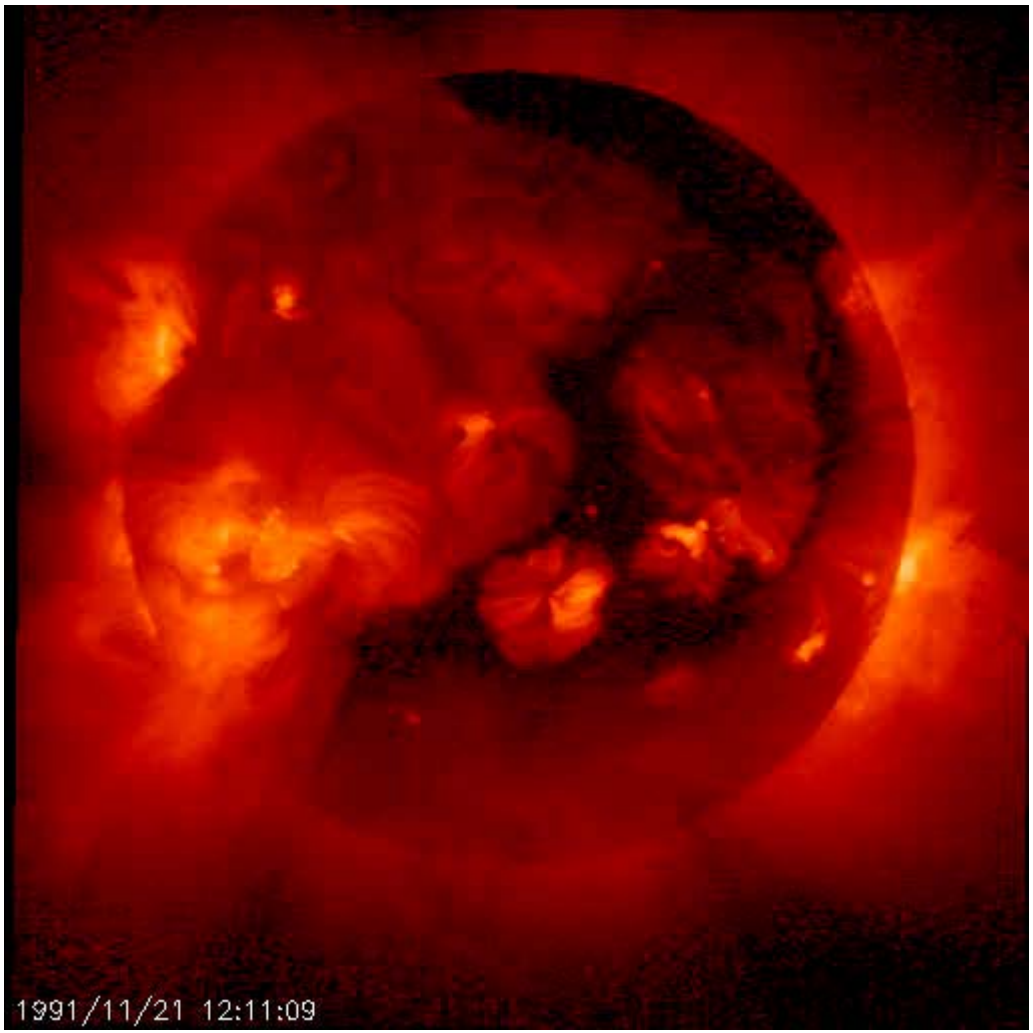


Fletcher & Hudson, Solar Physics, 2001

Active Region Classification (Mt. Wilson)

- ALPHA: A single dominant spot, often linked with a plage of opposite magnetic polarity.
- BETA: A pair of dominant spots of opposite polarity (Bipolar, i.e., a leader and a follower).
- GAMMA: Complex groups with irregular distribution of polarities.
- BETA-GAMMA: Bipolar groups which have more than one clear north-south polarity inversion line.
- DELTA: Umbrae of opposite polarity together in a single penumbra.

Sunspots, Active Regions, Prominences



This Yohkoh/SXT movie shows the development of solar activity from minimum to maximum. Both coronal holes and active regions are seats of solar mass emission in the form of solar wind and coronal mass ejections that impact Earth's magnetosphere

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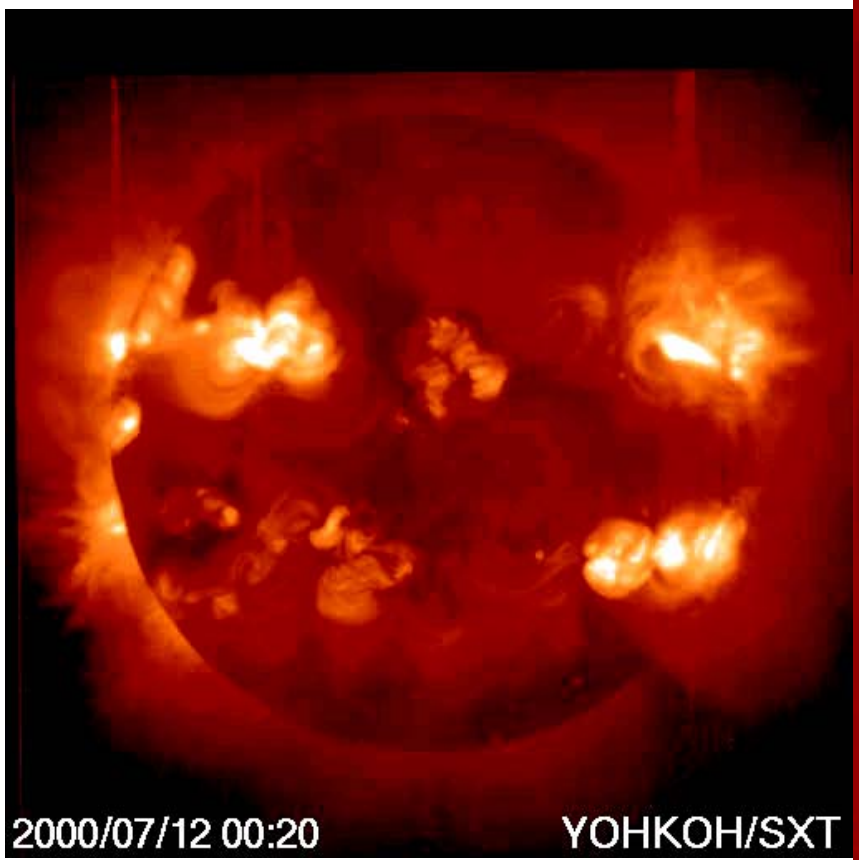
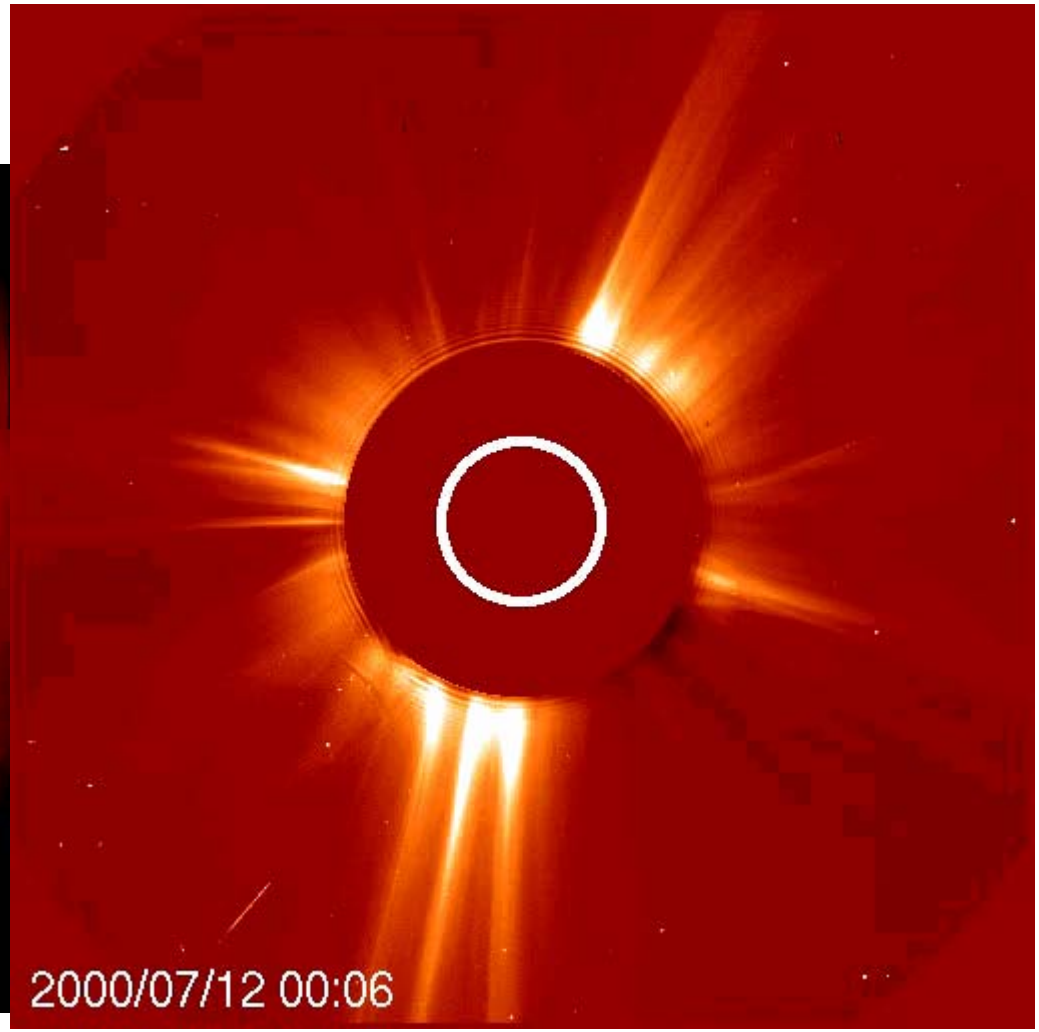
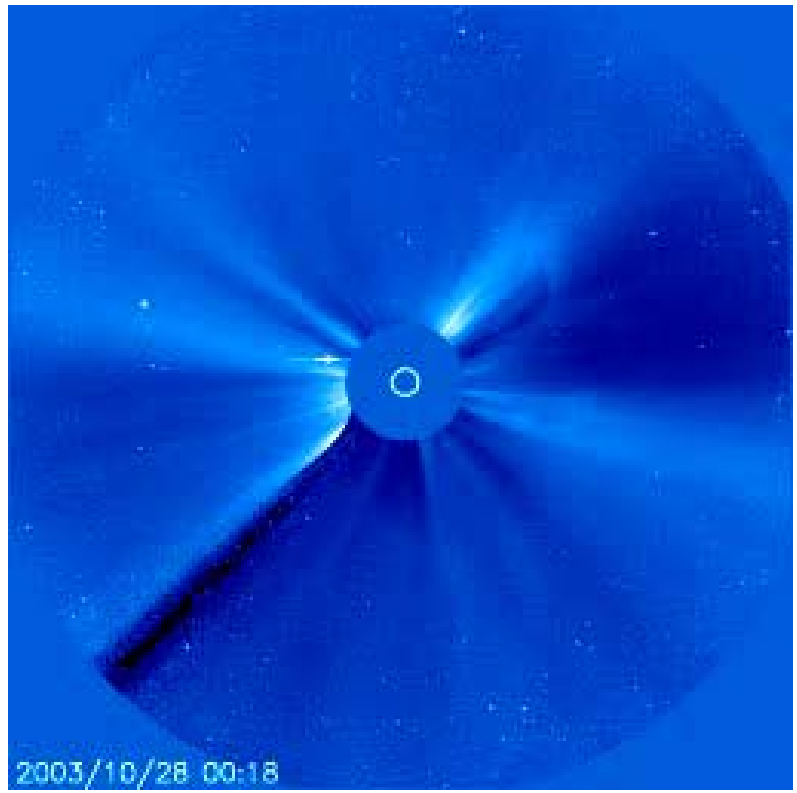
CMEs with corresponding changes in active regions





High Energy Plasmas & Particles

This movie taken by the C3 telescope on board the SOHO coronagraph shows how CMEs affect our ability to operate in space. The coronal mass ejections appearing on the solar disk accelerated solar energetic particles that reached the SOHO spacecraft in tens of minutes and blinding the detectors (the "snow storm" effect). Further observations of CMEs were hampered by this for several hours. The CMEs themselves arrived at Earth in less than a day to cause superintense geomagnetic storms.

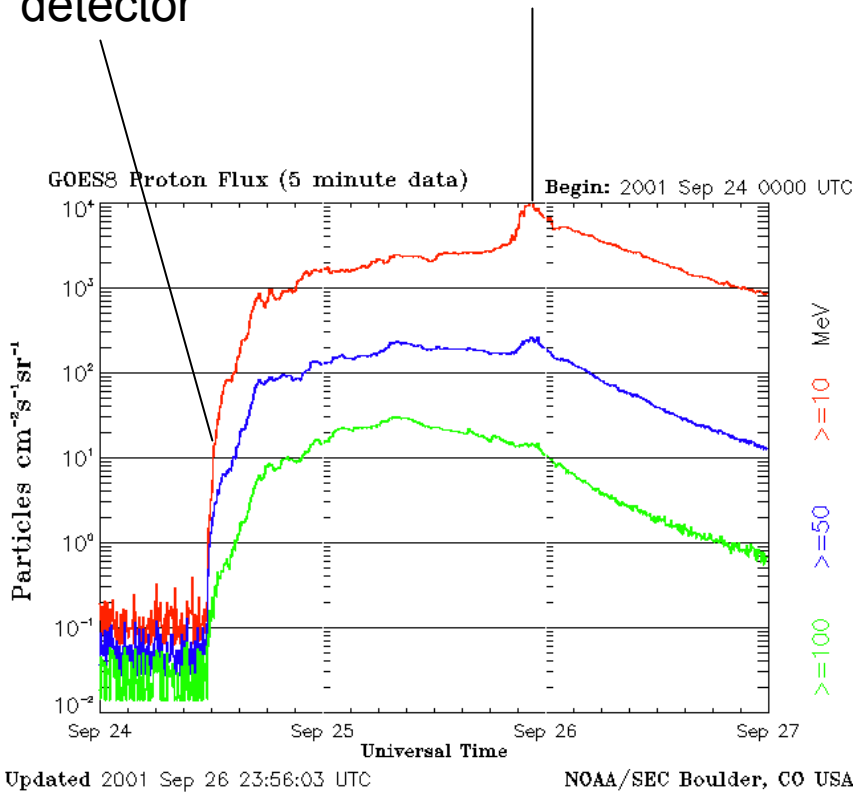


Radiation hazard is of primary concern for space missions

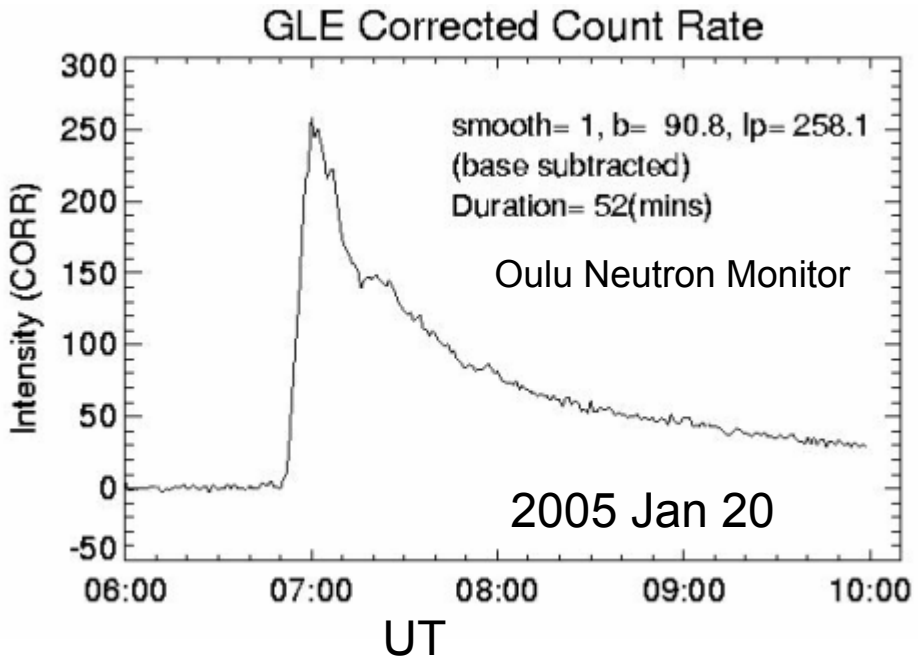
CME-related Energetic Particles

SEPs accelerated when the shock is far away from the detector

Energetic Storm Particle (ESP) events: acceleration when the shock is at the detector

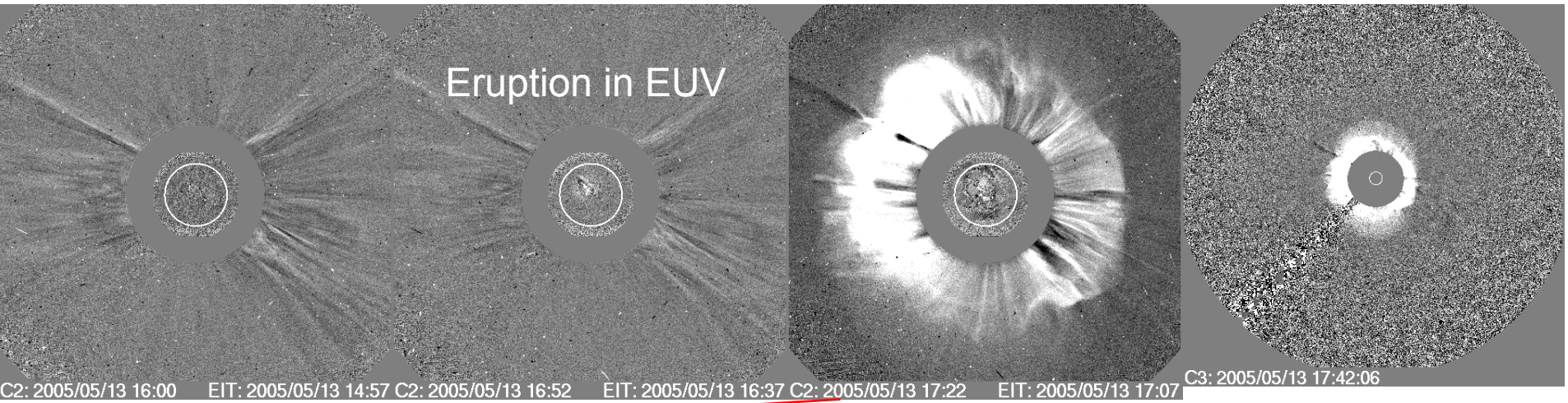


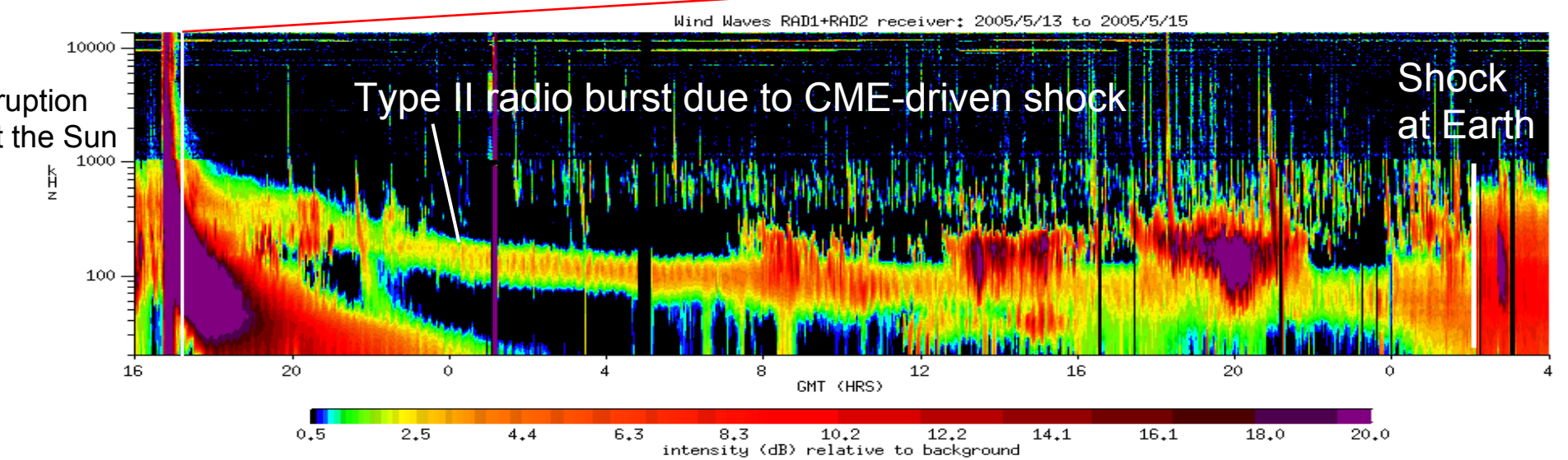
SEPs with ground-level enhancements



Sun to Earth Event

Halo CME

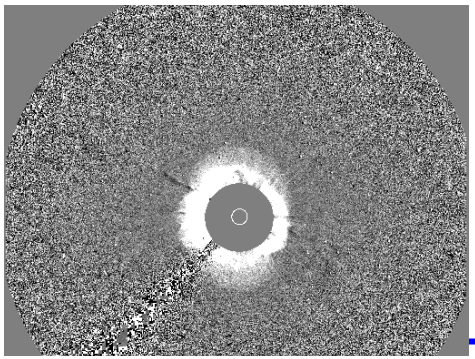


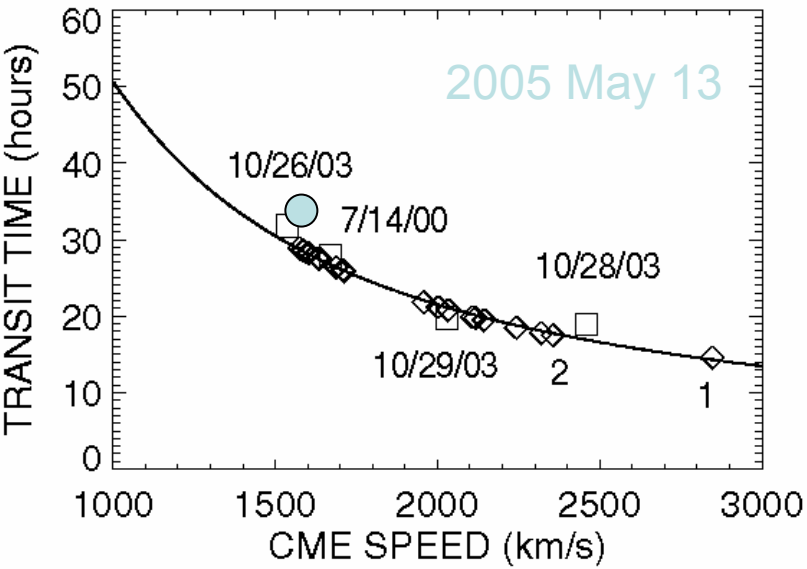


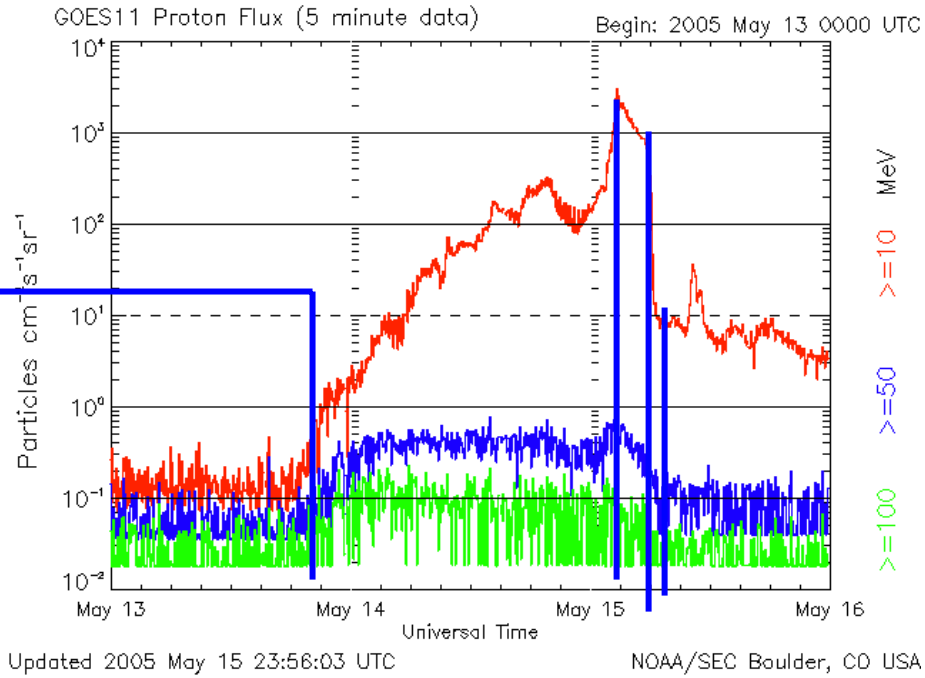
ruption
t the Sun

SEP Event

Onset when CME is >10 Ro away from the Sun. Very intense ESP – intensity jumps from 100 pfu to 3000 pfu. Behind the shock, the intensity drops precipitously from 1000 to 10 pfu. A gradual drop for ~3h and a sudden drop in <30 min. This marks the MC boundary? There is a spike inside the MC.



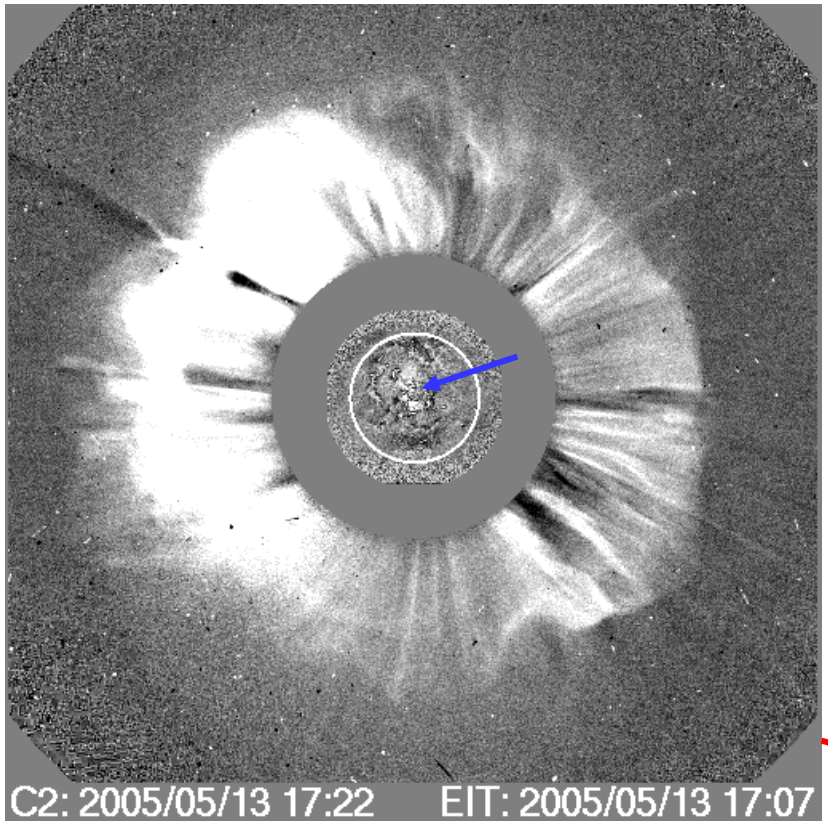


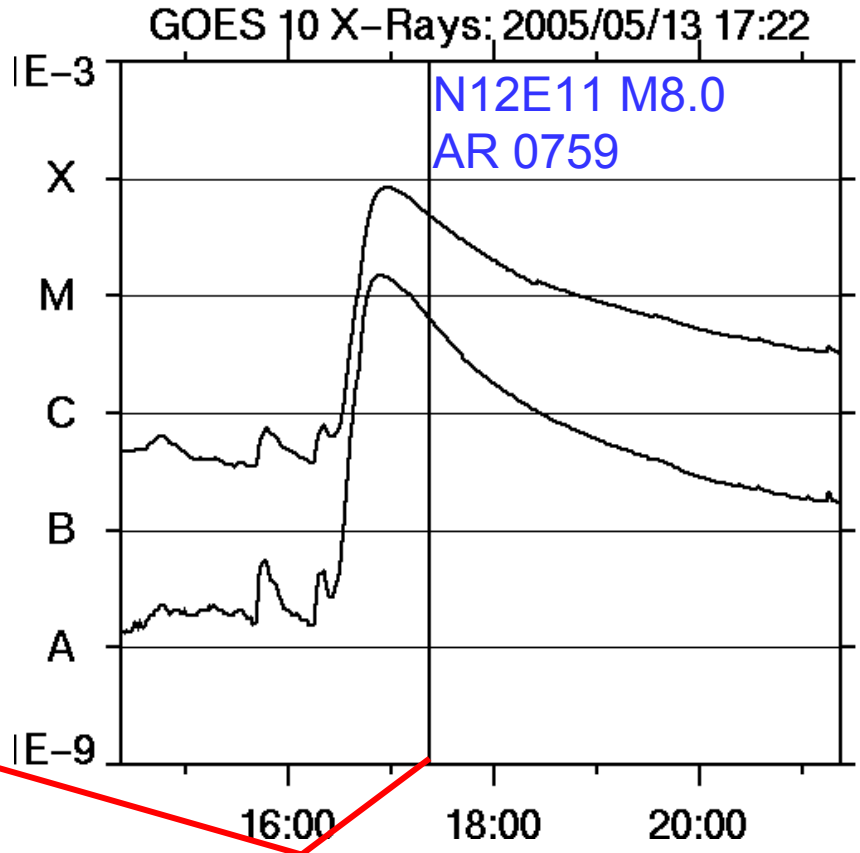


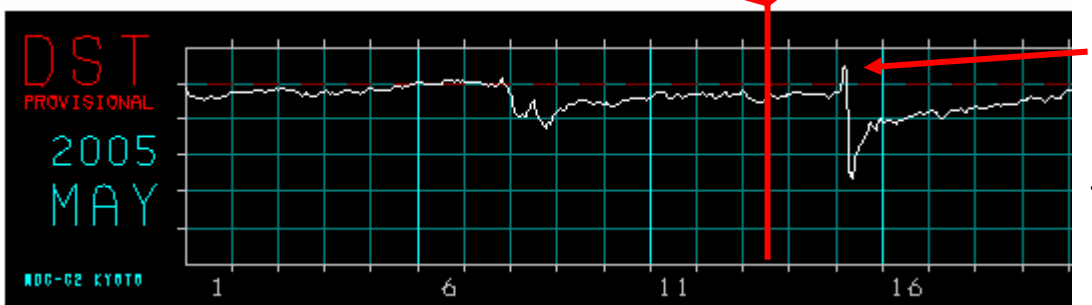
The same shock accelerates protons to > 100 MeV

Gopalswamy

Halo CME impact produces Geomagnetic Storm







Dst: +45 to -263 nT
Strong shock
SW speed jumps from 500 to 1000 km/s

2006 Dec 11

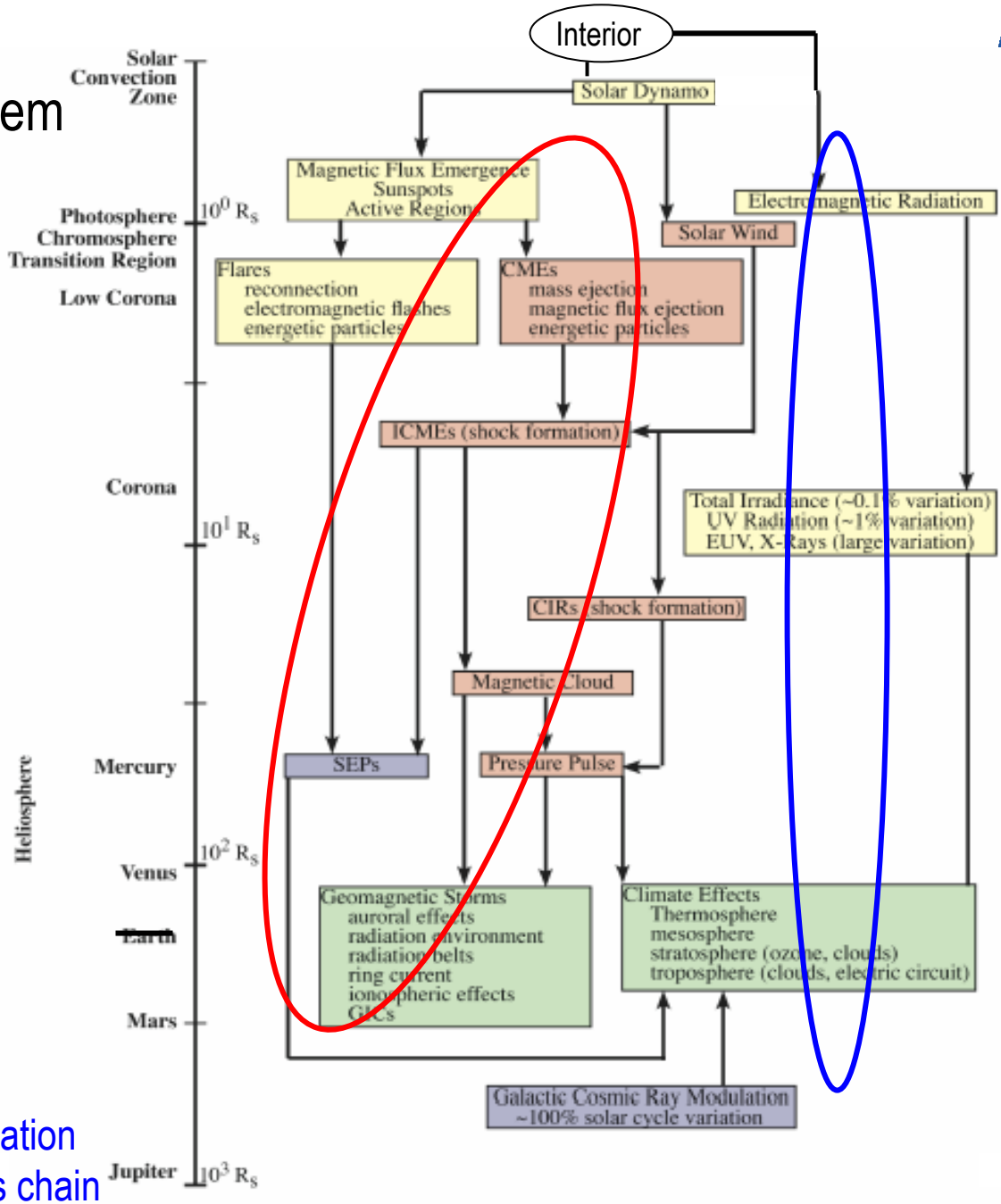
Solar Variability & its Impact on the Solar System

Sun puts out -
electromagnetic radiation
(blackbody + flare)
and mass
(solar wind, CMEs, SEPs)

Mass Chain:
CMEs
Solar Wind
SEPs

Aspects of CMEs related to Space Weather :
- ability to cause Geomagnetic storms (geoeffectiveness)
- ability to drive shocks that accelerate SEPs (SEPeffectiveness)

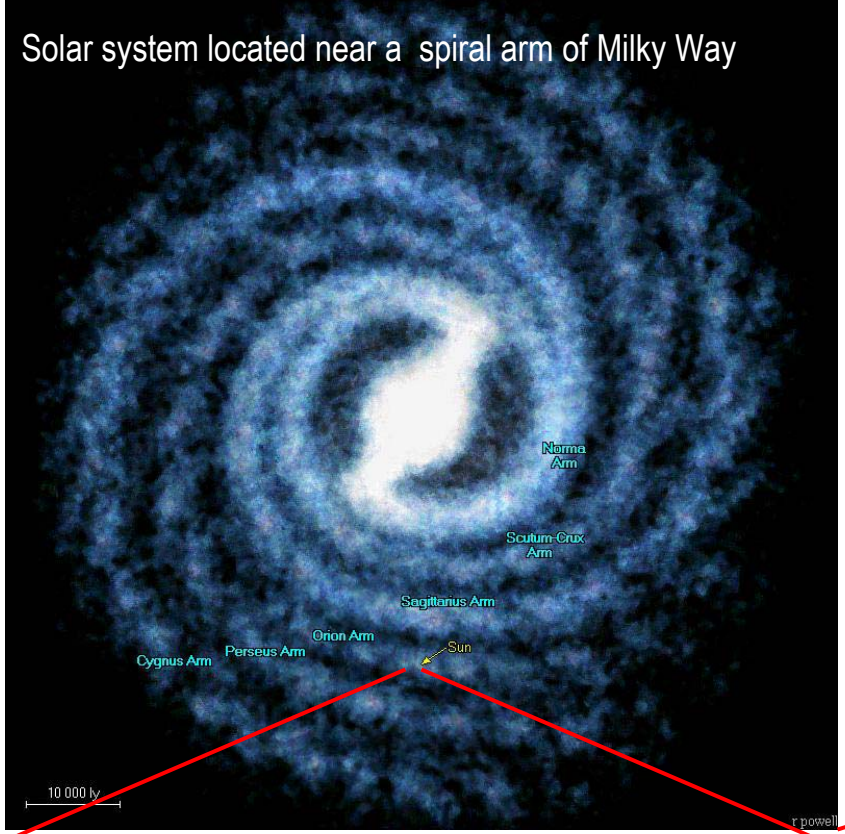
Climate effects mainly from variability in electromagnetic radiation with a contribution from the mass chain



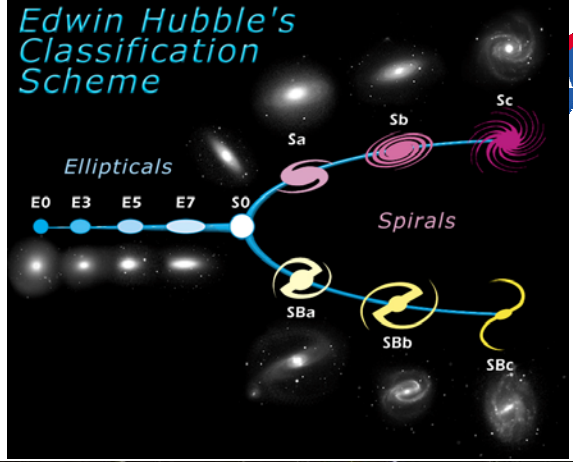
Additional Slides

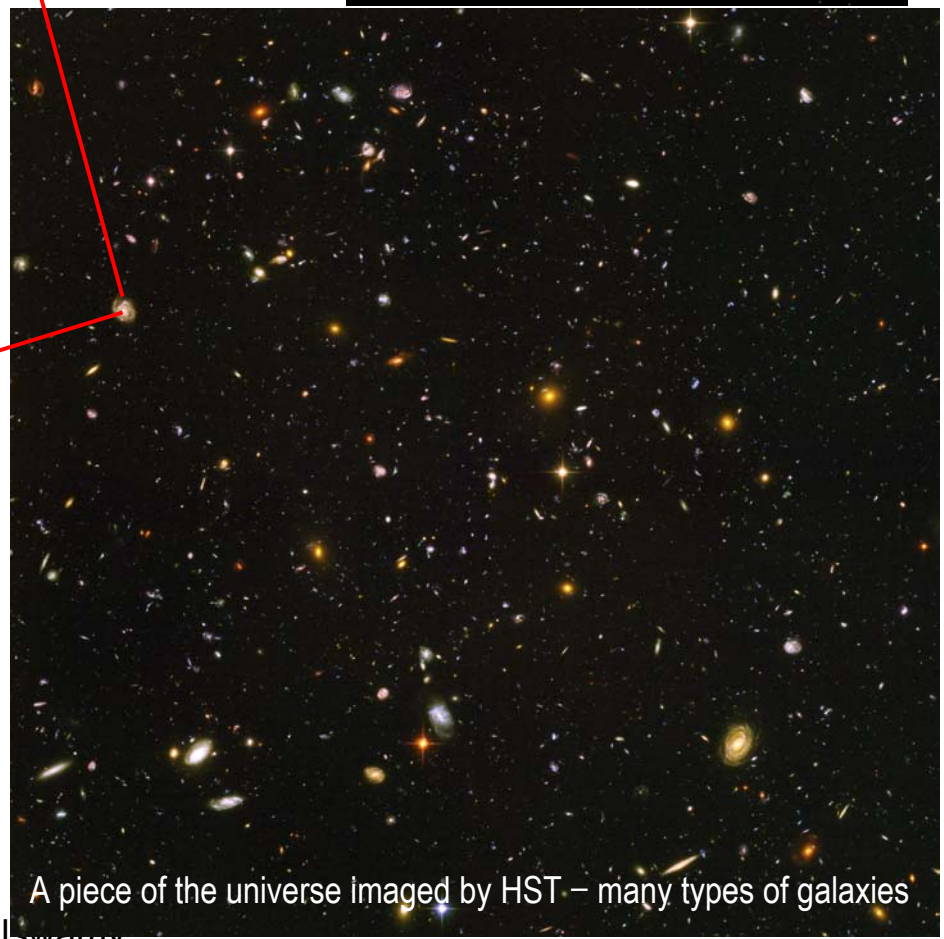
Abundance Comparison

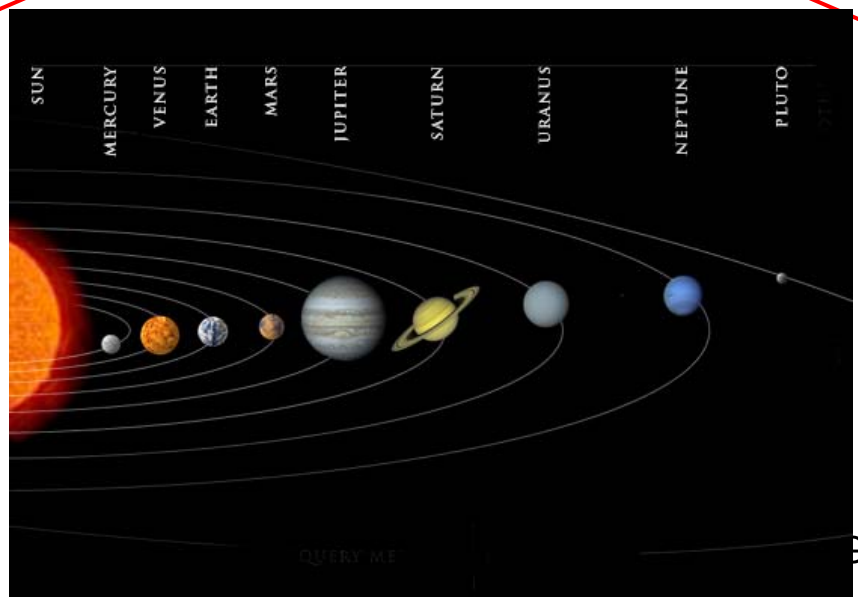
Element	Atomic Number	Photospheric Abundance	Coronal Abundance	Solar Wind Abundance
H	1	1	1	1
He	2	0.1	0.1	0.04
C	6	9.00E-04	2.40E-04	2.3-4
N	7	8.00E-05	3.90E-05	7.90E-05
O	8	1.00E-04	2.50E-04	5.30E-04
Ne	10	2.00E-04	3.50E-05	9.00E-05
Na	11	2.10E-06	2.70E-06	
Mg	12	3.80E-05	3.70E-05	
Al	13	3.00E-06	2.70E-06	
Si	14	5.00E-05	3.00E-06	1.20E-04
S	16	1.50E-05	8.60E-06	
Ca	20	2.30E-06	2.9E-6	
Fe	26	4.70E-05	3.90E-05	1.00E-04
Ni	28	1.80E-06	2.2E-6	



M83 – a galaxy similar to ours

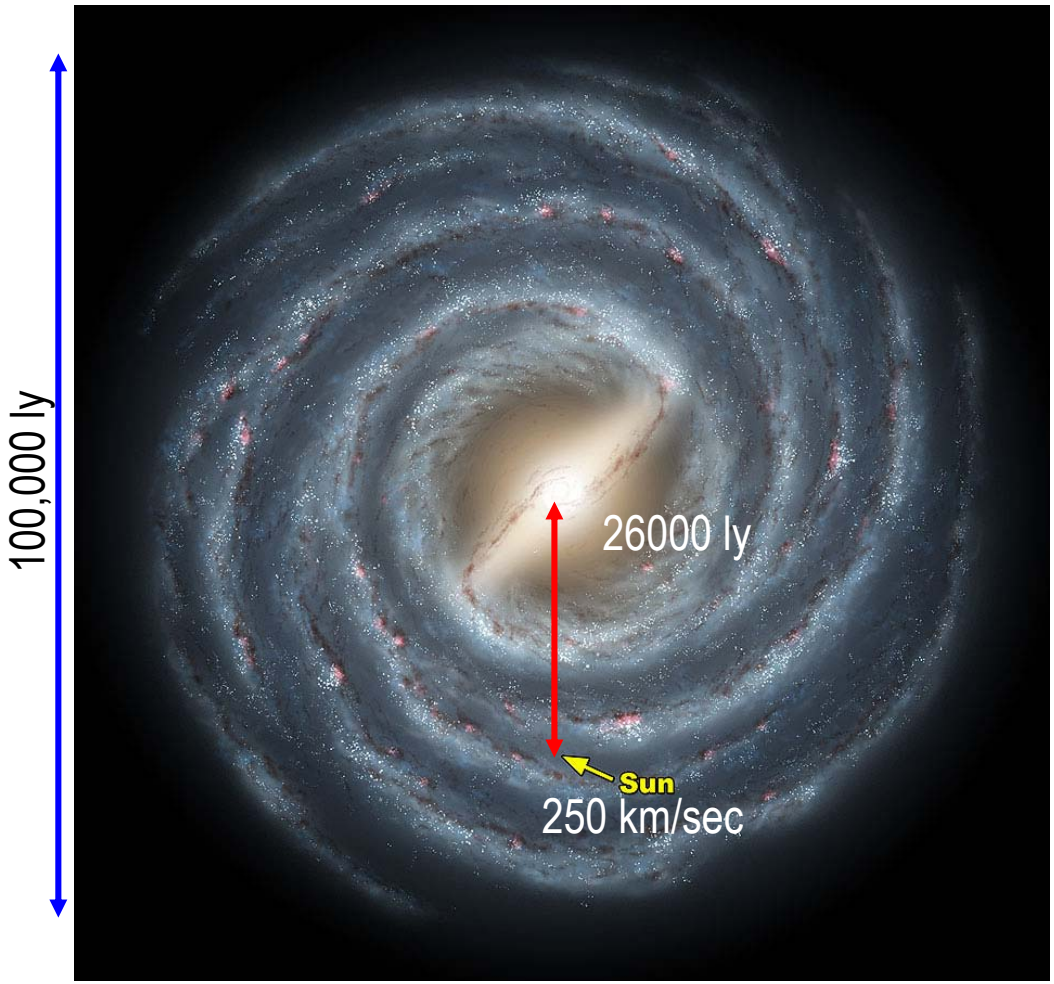






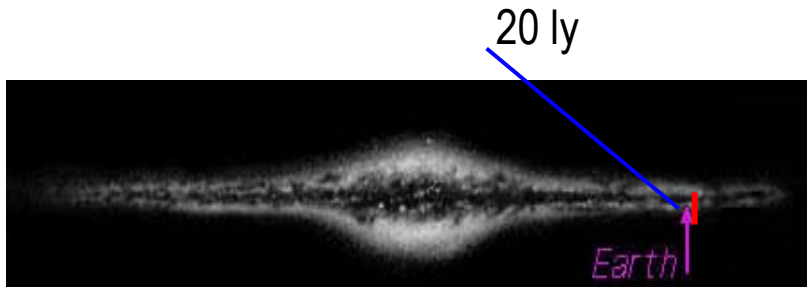
Our place in the Milky Way

sun is located at a distance of 26000 ly from the galactic center & slightly displaced from the galactic plane (by 20 ly)



Orbital period (Galactic year) 220 million years

Galaxies:
- Basic units of larger, organized structures
- Sites of star formation from raw gas
- Factories synthesizing heavy elements from Hydrogen & Helium



Mass of our galaxy ~10^{12} $M_\odot$

stars (~ 400 billion) and their planets, and thousands of clusters and nebulae, gas, dust

1 ly = 10^{13} km, distance traveled by light in one year

Solar Fuel

- Protons (hydrogen nuclei) fusing to form alpha particles (helium nuclei) and releasing energy in the process seems to be the primary source of energy for the Sun
- But what is the origin of H and He in the Universe?
- One of the acceptable answers is the Big Bang
- The formation of H and He occurs as the universe starts expanding after the Big Bang
- A definite ratio between H and He results from Big Bang
- These become key ingredients in the galaxies formed eventually

Big Bang

- Hydrogen, helium, and some lithium formed moments (~ 3min) after the Big Bang

T = Temperature (K); k = Boltzmann constant; kT = thermal energy; 1 ev ~10,000 K
1 MeV = 10^6 eV ~ 10^{10} K or 10 BK

History of the Universe according to the Big Bang theory

Cosmic time	Temperature	Events
$t \approx 10^{-4}$ s	$kT \approx 10^2$ MeV	Quarks form neutrons and protons
$t \approx 1$ s	$kT \approx 1$ MeV	Neutrinos decouple
$t \approx 4$ s	$kT \approx 0.5$ MeV	Electron–positron annihilation
$t \approx 3$ min	$kT \approx 0.1$ MeV	Helium and other light nuclei formed
$t \approx 3 \times 10^5$ years	$kT \approx 0.3$ eV	Atoms formed and photons decouple

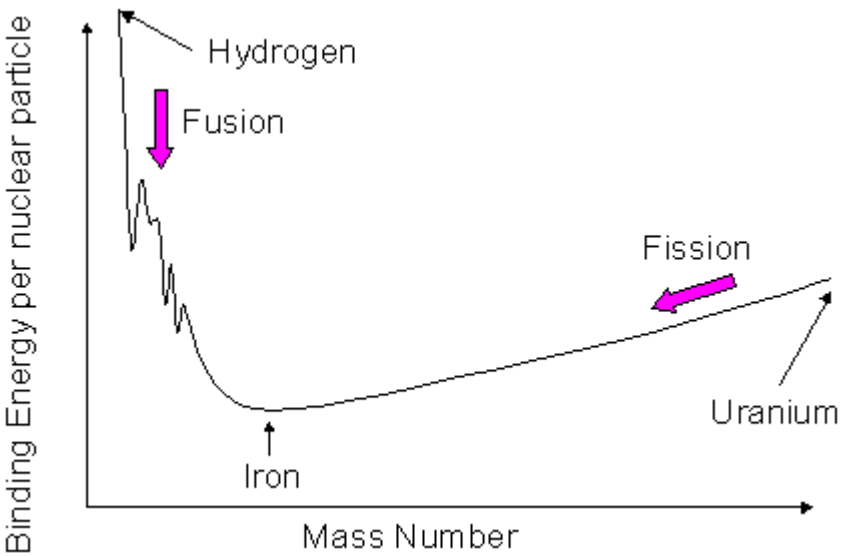
10^9 K

Nucleosynthesis: Big Bang, stellar fusion, neutron capture

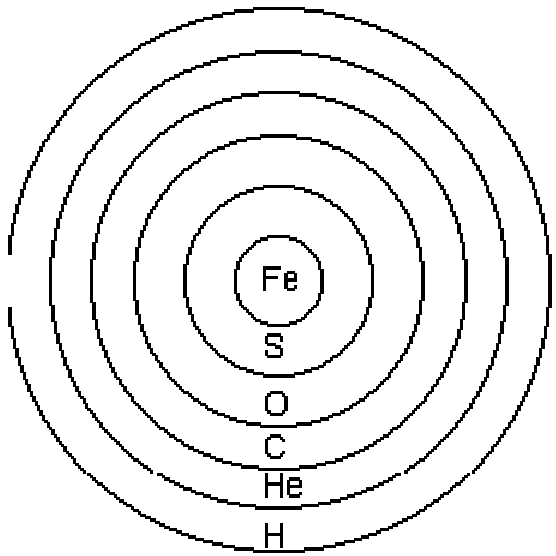
- Hydrogen, helium, and some lithium formed moments (~ 3min) after the Big Bang; how about heavier elements found on Earth and in the solar system?
- Fusion in stars produces elements up to ^{56}Fe. Beyond ^{56}Fe, fusion reactions do not release energy
- Slow (or s) process of neutron capture followed by beta decay can produce heavier elements: e.g., $^{56}\mathrm{Fe} \rightarrow {}^{57}\mathrm{Fe} \rightarrow {}^{58}\mathrm{Fe} \rightarrow {}^{59}\mathrm{Fe}$ (3 successive neutron captures), followed by $^{59}\mathrm{Fe} \rightarrow {}^{59}\mathrm{Co}$ (beta decay).
- S-process goes on until ^{208}Pb and ^{209}Bi are reached; no more slow neutron capture possible because the new nuclei decay fast before they can capture neutrons.
- The rapid (or r) process breaks past ^{208}Pb. The stable actinides may be produced directly from a neutron-rich precursor, or from α-decay of even heavier elements. [needs lots of neutrons – wind from neutron stars?]

We are stardust!

Elements up to Li can be explained as a consequence of the Big Bang. Higher mass elements up to Fe can be explained by fusion reactions taking place in the interior of stars. Heavier elements up to Uranium seem to be created in novae and super novae (neutron capture makes them in Asymptotic Giant Branch (AGB) stars; convection brings them to the surface and supernovae to the ISM; r –process in winds from neutron stars). Fe is the most stable element. So, all the elements our body were made in the interior of stars.



The universe is slowly becoming Fe rich



Structure of massive stars

Birthplace of the Sun: a dark cloud like this

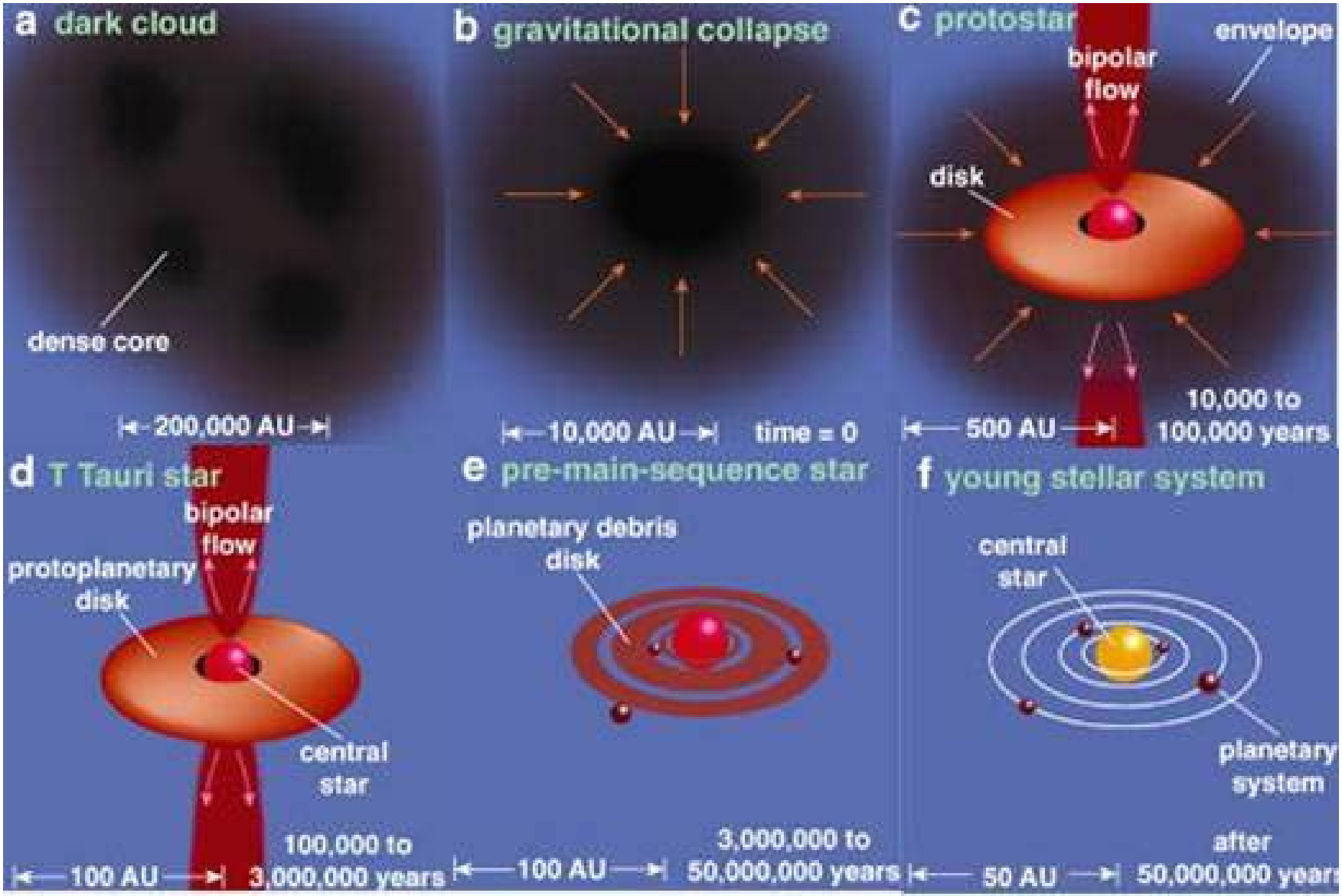
The "Black Cloud" B68
(VLT ANTU + FORS1)

ESO PR Photo 20a/99 (30 April 1999)

2006 Dec

1 AU = 1.5×10^8 km

Early life



Some Vital Statistics of the Sun

- Average, middle aged star (4.5 billion years) on the main sequence
- One among the 400 billion stars in the Milky Way
- The only star that is observable in great detail: units of measurement for stellar quantities
- Likely to become a white dwarf at the end
- Composed of ~72% hydrogen, ~26% helium and ~2% of all other chemical elements (most notably those up to oxygen) in gaseous form.
- Energy source: nuclear fusion at a temperature of ~14 MK
- Approximate sphere of radius ~696000 km (compare Earth radius 6400 km)
- Rotation rate: $13.45 - 3.0 \sin^2\varphi$ deg per day [φ = latitude] or rotation period ~26.7 days at the equator
- Rotation speed ~ 2 km/s at the equatorial photosphere
- mass ~2×10^{30} kg
- Average density ~ 1.4 g/cm^3
- Gravitational acceleration 274 m/s^2
- Luminosity (energy radiated by the sun in one second) $L_\odot$: 4×10^{26} W → 1.4 kW/m^2 at Earth's orbit
- Surface temperature ~5770 K [at this temperature a black body radiation peaks in visible light]
- An extended atmosphere known as corona at 2 million K → emits predominantly in X-rays
- Sun is at an average distance of ~1.5×10^8 km from Earth
- Sun emits the entire electromagnetic spectrum

Local and Global Views of the Sun

Sun is studied in two ways:

Global view (Sun as a star – how it evolved over billions of years): Such a view also helps understand other stars and provides a convenient reference for many stellar parameters such as size, mass, luminosity,...

Local view: The only star close enough to view the spatial and temporal variations. e.g. sunspots, active regions, faculae, spicules, granulation, plumes, prominences, coronal holes ...

Sun is the basis for all life on Earth: the Sun shines and life thrives

The variability of the solar emissions also affect life on Earth as a source of space weather and possibly climate change. Understanding the solar variability in terms of the known physical laws is a major effort by a large community of solar and solar terrestrial physicists.

Acknowledgments

- Some slides on flares borrowed from G. Holman
- Many images from various NASA web sites